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# Geology of the Red Valley Sandstone in Forest and Venango Counties, Pennsylvania

Dana R. Kelley

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF INTERNAL AFFAIRS
John K. Tabor, Secretary

BUREAU OF
TOPOGRAPHIC AND GEOLOGIC SURVEY
Arthur A. Socolow, State Geologist

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# Geology of the Red Valley Sandstone in Forest and Venango Counties, Pennsylvania

by Dana R. Kelley
Staff Geologist
Pa. Geological Survey

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# GEOLOGY OF THE RED VALLEY SANDSTONE IN FOREST AND VENANGO COUNTIES, PENNSYLVANIA

By

Dana Kelley

## ABSTRACT

Economic geological facies are delineated within the widespread Red Valley sandstone utilizing scattered wells for which reasonably accurate geological and engineering data are available. Basin type gray siltstones and shales grade within a short distance into narrow nearshore belts of clean, porous sandstone which correspond to areas of greatest economic potential. Shelfward from these belts the sandstones gradually become more laminated and cemented, forming widespread trends of generally marginal economic significance. Farthest shelfward the zone breaks up into interbedded sandstones, siltstones, and shales, of negligible profitability. The distribution of the various facies in time indicates the presence of predictable Upper Devonian transgressive and regressive shelf edge fluctuations, useful in both exploration and exploitation.

The amount and type of pore-plugging fines, and secondary silica, carbonate, and clay cement varies both vertically within the Red Valley pay zone, and laterally in relation to the different facies. Accompanying a decrease in grain size, sorting and porosity, secondary interstitial quartz, kaolinite, and ankerite cement increase from the porous belt toward the nonporous shelf to the east. Detailed consideration of these variations could significantly improve completion and subsequent secondary recovery results.

## INTRODUCTION

There is a definite need for establishing a basic geological framework for productive intervals in Pennsylvania's oil and gas sandstones, from which advanced engineering and geological techniques and studies can be applied to improve the methods and economics of hydrocarbon exploration and exploitation. To fulfill this need the Pennsylvania Geological Survey has initiated a multistage project to gain an understanding of the geological framework of the Upper Devonian, the distribution and relationship in time and space of the various important reservoir zones, and the general variation in petrography and mineralogy of these zones so important in programing economic exploration, exploitation, and secondary recovery operations. Current investigations are directed toward establishing correlations, a prerequisite to meaningful petrographic analyses. Progress reports will be presented to make information available as soon as possible to the industry. This study is the first such progress report.

The objective of this report is to present data on the shallow Devonian sandstones that may have immediate practical application for the oil operators working in Pennsylvania. Additional geological information having potential significance in the discovery and extraction of economic quantities of hydrocarbons will also be brought to the attention of industry. It is hoped that the presentation of this material will stimulate greater industry investigation, increased industry cooperation, and improved methods of data acquisition and preservation.

Availability of reasonably good mechanical logs and some cable tool samples, Baker Core biscuits, and chip core fragments has permitted the Survey to make a preliminary examination of the stratigraphy and petrography of the productive Red Valley sandstone, one of the prominent pay horizons of the Upper Devonian, Riceville Group, Venango sand sequence in northwest Pennsylvania (Figure 1). Table 1 contains the general stratigraphic section of the shallow formations of the area. Various reports have described the generalized surface and shallow subsurface geology of these formations within and bounding the area of the report (Ashley, 1938; Dickey, 1941; Dickey and others, 1943).

Oil production in the Red Valley sandstone, or the Lytle sandstone as it is sometimes designated in portions of the subject area, was first developed on the Lytle Farm, approximately 3 miles south of Pleasantville, around 1890. Initial Red Valley production occurred in the Red Valley field, just southeast of Pittsville to the south of the mapped area in 1885. There is some doubt as to the exact correlations between the producing sands at the Lytle farm and the Red Valley field. Both sands occur in the interval between the Venango First and Venango Second sandstones. The Lytle producing zone is believed to be slightly lower stratigraphically than the Red Valley zone (Dickey and others, 1943, p. 87-88), and possibly the zone at the Red Valley Field to the south represents the Red Valley II sandstone of this report. However, sufficiently detailed correlations can be made within the subject area to define specific pay intervals. Until correlations to the south can be detailed, the name Red Valley is tentatively used for that pay zone generally known as Red Valley in the subject area and which is correlative with the Lytle sandstone at Lytle farm.

Considerable general information on the Red Valley sandstone (or correlative zones of other names) has been published. Many of the references cited at the end of the report discuss, at least in part, this shallow Upper Devonian pay zone and local areas of production from this horizon. However, little attention has been directed toward geological differentiation of prolific and marginal production from the zone, the anomalous occurrence of dry holes, and whether there could be a logical geological pattern for the distribution of good, marginal, and nonpro-

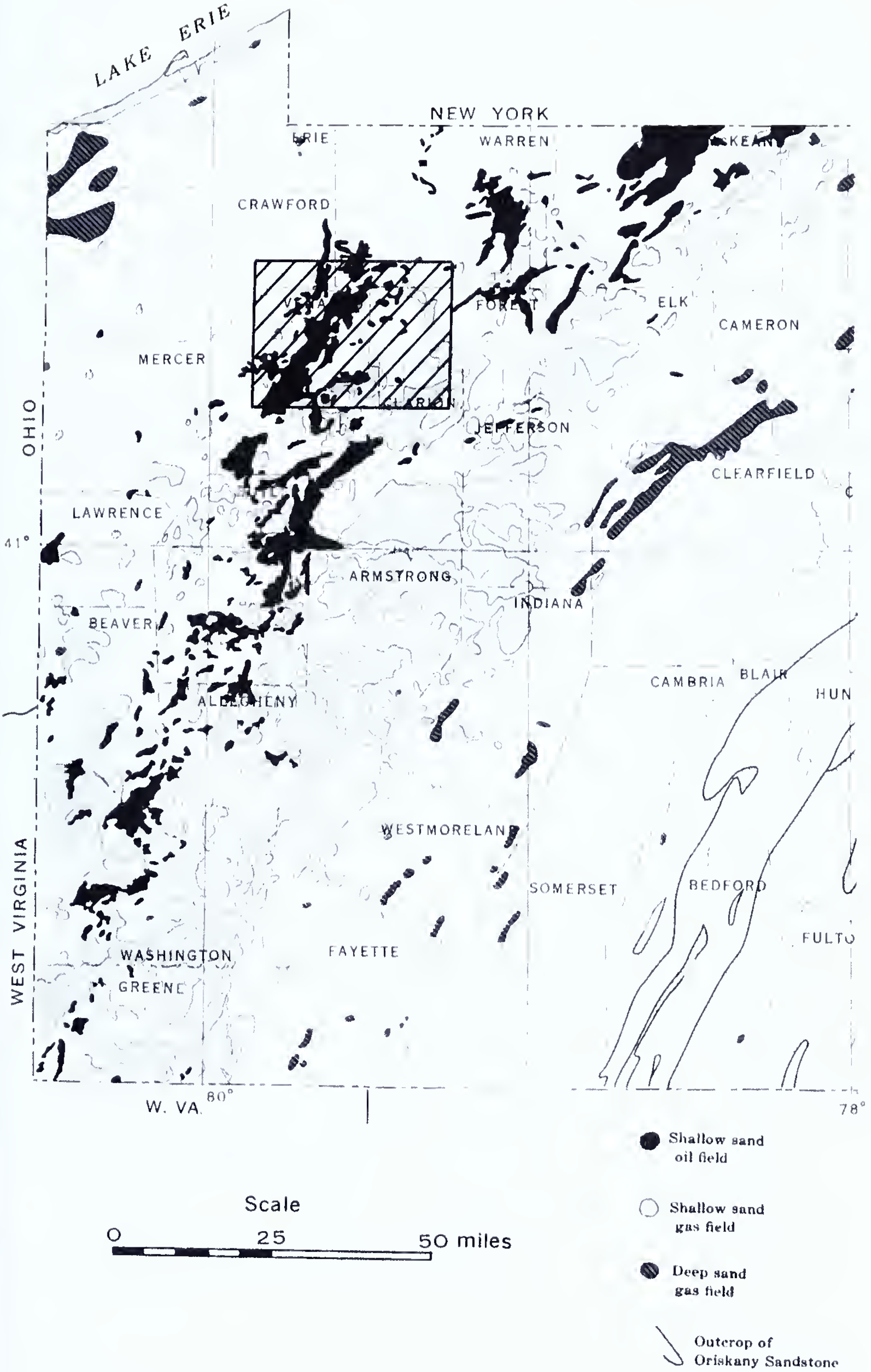

Figure 1. Oil and gas fields index map of western Pennsylvania showing area of report.

ductive wells. The purpose of this report is to present recently obtained data and interpretations which indicate that a geological pattern does exist, that the distribution of profitable and marginal producers, as well as dry holes, may be reasonably anticipated, and that the probable cause

Table 1.—**Generalized Stratigraphic Section of Venango District, Pennsylvania.*

Locally exposed in Venango District

| Rock Unit | Lithology | Thickness (feet) |
|---|---|---|
| PENNSYLVANIAN SYSTEM | | |
| Conemaugh Group | shales, thin-bedded sandstones, coals | 250 + |
| Allegheny Group | shales, sandstones, limestones, coals | 300 |
| Pottsville Group | sandstones, shales, limestones, coals | 250 |
| ——Unconformity—— | | |
| MISSISSIPPIAN SYSTEM | | |
| Pocono Group | sandstones, shales, basal Shenango Sandstone Formation | 0-300 |
| Cuyahoga Group | shales, sandstones | 100-160 |
| Corry Sandstone | sandstone, minor shale | 12-30 |
| Cussewago Group | shales, siltstones, sandstones | Undifferentiated in Subsurface 150-250 |
| ——Gradational Boundary—— | | |
| DEVONIAN SYSTEM | | |
| Riceville Group | gray and red-brown shales, siltstones | |
| Cattaraugus Formation | | |
| Venango sand sequence | | |
| First sand | sandstone, minor shale | 0-50 |
| shale | shale, minor siltstone and sandstone | 20-50 |
| Red Valley II | sandstone, minor shale | 0-40 |
| shale | shale, minor siltstone and sandstone | 10-30 |
| Red Valley | sandstone, minor shale | 0-25 |
| shale | shale, minor siltstone and sandstone | 15-40 |
| Second sand | sandstone, minor shale | 0-30 |
| Amity shale | shale, minor siltstone and sandstone | 50-80 |
| Third sandstones | 3-5 sandstones, interbedded siltstone and shale | 75-95 |
| shale | shale, minor siltstone | 90-110 |
| Conneaut Group | | |
| "Pink Rock" | gray-red and green-gray shales and siltstones | 325-250 |
| Warren-Bradford | sand sequence | |

* General nomenclature of area adapted for use in this report. Names subject to change pending current correlation studies in progress.

for the type of resultant production, or lack of it, can be geologically ascertained.

The data and interpretation presented are limited to the availability of modern mechanical logs and adequate samples. Details and refinements will develop through additional new material. It is hoped that this report will stimulate acquisition and interpretation of detailed geological information by the local industry, and an appreciation that emphasis on geology can result in practical data so necessary to obtain more economically profitable hydrocarbons for less cost.

## ACKNOWLEDGMENTS

The Pennsylvania Geological Survey expresses its appreciation to the many oil operators, in and bounding the area of study, that supplied mechanical log and sample control; particular thanks are extended to Mr. Gale Wiesner of Quaker State Oil Company, Bradford, Pa., Mr. Raymond Zoerkler, Pennzoil Company, Bradford, Pa., and Dr. O. D. Weaver, Weaver Oil and Gas Corporation, Butler, Pa. The Survey acknowledges the fine cooperation of Mr. William K. Overbey, Jr., at the Morgantown Petroleum Research Laboratory, U. S. Bureau of Mines, Morgantown, West Virginia in affording some of the data and analyses used in this report. Credit is given to Miss Lillian Heeran and Miss Virginia Fairall of the Survey who spent considerable effort in preparing the illustrations. The author appreciates the help, through useful suggestions, made by Survey members: W. G. McGlade, D. M. Lapham, and D. M. Hoskins, who critically read the manuscript.

## GEOLOGICAL SETTING

The Red Valley sandstone is a prominent sandstone member of the Venango sand sequence of the subject area. It is present locally at the surface along the erosional valley of the Upper Allegheny River in the north part of the mapped area. The Red Valley sandstone occurs in the shallow subsurface at depths ranging from a few hundred feet to approximately 900 feet under hills in the south portion of the mapped area.

The Venango sand sequence is a complex grouping of tan to light gray, very fine to coarse sandstones and minor conglomerates of variable thicknesses separated by gray, black, and occasionally varicolored siltstones and shales. It represents the highest stratigraphic occurrence of significant sandstones in the Devonian of the area. The top of this sequence is positioned approximately 100 feet below the postulated gradational Devonian-Mississippian contact. The sequence occurs some

350 feet above the next prominent Upper Devonian productive sequence of sands, the Warren-Bradford sequence, and is separated from these sands by an interval of gray-red and green-gray unproductive siltstones and shales commonly known by the driller's name "Pink Rock."

The Venango sand sequence was deposited along the southeastern flank of the Upper Devonian Appalachian Basin. The prominent sandstones which distinguish the sequence are absent basinward to the northwest, where along the Ohio-Pennsylvania boundary, the interval is represented by marine, gray and black shales. Increased sandstone and decreased shale content accompanies a slight increase in thickness shelfward to the southeast. In this direction the prominent pay sandstones of the subject area thin and become interbedded with shales and siltstones. As a result, they lose their identity in a shelf section of multiple, alternating, thin, conglomeratic, silty sandstones, siltstones, and silty and sandy shales, frequently varicolored.

## MISCORRELATION OF PAY-ZONE NAMES AND INADEQUATE WELL RECORDS

Correlation in the Venango sequence in the subject area, and in general in Pennsylvania, has been based largely on local occurrences of prospective and productive horizons. Descriptive and locality names applied for convenience to these zones by drillers, and other geologically untrained operators, ever since discovery and initial development of oil pools in the late 1800's have been generally maintained to this date. No serious attempt at unraveling a profusion of local names has been made. Plate 1 affords a few examples of confusion and miscorrelation between names. A few, but by no means all, of the local names for important reservoir zones are indicated in parentheses following the name tentatively assigned to the zone in this paper. Figure 2 also illustrates the problem of name miscorrelation, i.e. Red Valley and Second sand, Salt sand and Second sand, position of the Third Stray sand, and Third sand and Fourth sand.

Because of exceptionally poor well data reporting and preservation in Pennsylvania, together with delayed application of modern logging and exploration methods, it was not possible until recently to attempt detailed correlations in the Venango sand sequence. Excellent prospects for new discoveries and pool extensions, masked by miscorrelation, exist today as well as they did more than 20 years ago when the problem was given nationwide attention (Sherrill, 1944).

Figure 2 illustrates the ambiguity that can result from the use of scout information (release of mechanical logs being rare) in defining tops and

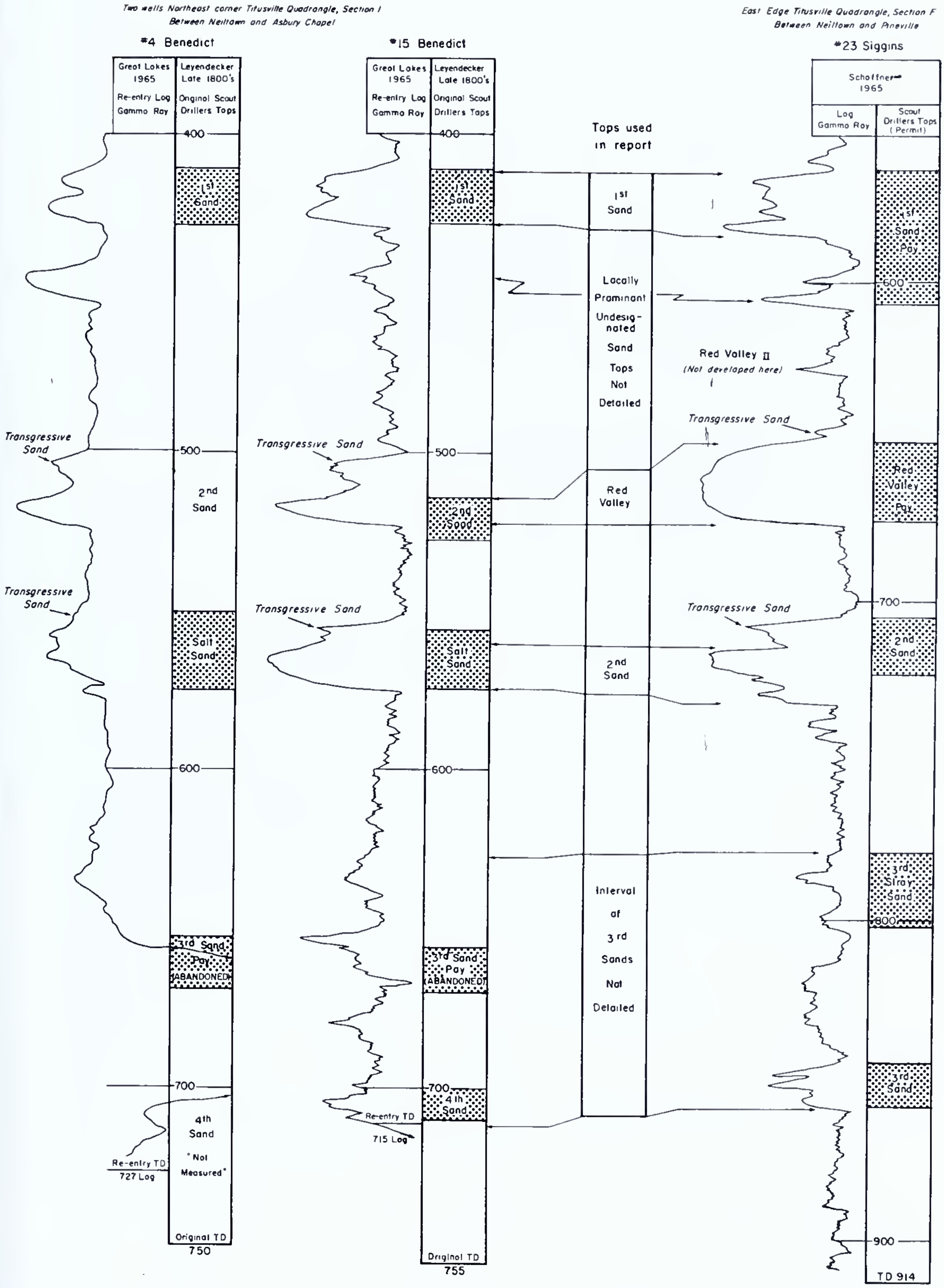

Figure 2. Examples of tops used for some Venango sands in the Pleasantville Field area.

bottoms, and subsequent resultant critical thicknesses and structure of some of the Venango sequence pay zones. The examples selected are not the best, but unlike the better examples, do illustrate many different factors of importance in establishing the occurrence of pay sands in an area. The No. 4 and No. 15 Benedict wells, drilled in the late 1800's, were recently re-entered and logged. Typical of records of early drilling, some prospective zones that were not major objectives at the time were not mentioned; for example, the sand at approximately 450 feet in the No. 4 Benedict. Other known pay zones, poorly developed in a well and therefore poorly regarded at the time, were given insufficient treatment in records; for example, the Red Valley (or what was called the Second sand) and the Fourth sand in the No. 4 Benedict were not deemed worthy of measurement. Consequently, the presence or absence of a pay sand cannot be satisfactorily ascertained from old records unless that sand was the prime objective. Such arbitrary interpretations apply to reports of shows and other critical well data, and have been continued in many cases in reports of present operations.

The No. 23 Siggins, a recent well, illustrates the arbitrary nature with which sand thicknesses are reported because of the absence of detailed geological work. The First sand thickness in this well is excessive and includes an underlying, separate sand.

The separation of a thin transgressive sand from the main Red Valley and Second sand pays has been arbitrarily reported in scout information. If there is a limited thickness of a diagnostic, continental, varicolored sand section between the transgressive sand and pay sand, or if this section has been missed by the driller, the total thickness of the pay zone incorporates all intervals; for example, the Second sand (or Salt sand) in the No. 23 Siggins. If, however, there is sufficient shale separation between the two, as shown for the Red Valley in the No. 15 Benedict, or if the transgressive sand is insignificantly developed, as for the Red Valley in the No. 23 Siggins, the sand thicknesses more nearly approximate true thickness. These and other factors reflect lack of close attention or appreciation of the geology of the pay sands, and result in interpretations of discontinuous and somewhat erratic patterns of distribution of total sand thickness.

As a result of the name confusion and miscorrelations, from incomplete or inadequate records, operators who utilize old or even new records or scout reports, without samples or mechanical logs, cannot be sure whether a specific sand in one area is the same as the similarly named sand in another area, whether the tops and thicknesses reported are reasonably accurate, or whether other important sands which were not recorded are present in the well. Unfortunately, examples of misnomers and incomplete or inadequate reports are sufficiently prevalent to suggest they may have impaired the geological validity of some past studies utilizing to a large degree drillers' records and scout information. The application and usefulness of production and completion statistics applied to these wells are similarly impaired. It is for these reasons that only adequately logged wells have been used in this report. It is hoped that subsequently these wells can be used for tying in older data for detailing and refining the regional interpretations presented here.

## CYCLIC DEPOSITION OF RED VALLEY AND OTHER VENANGO SANDSTONES

The pattern of deposition of the Venango sand sequence in time affords critical background information necessary in establishing the mechanism of emplacement and the distribution of the Red Valley and other Venango sandstone reservoirs.

### RELATIONSHIP OF RESERVOIR ZONES AND VARICOLORED CONTINENTAL CLASTICS

Plate 1 illustrates the relationship and distribution of the multiple pay horizons of the Venango sand sequence. Thin intervals of brown-red and gray-green siltstones and shales, in part mottled one with the other, are present above the First sand, Red Valley II, Red Valley, and Second sand. These intervals aid correlation and separation of the sandstones. The varicolored beds above the Red Valley and Second sand have been detailed across the area as shown in the section. It can be noted that these continental, or oxidized nearshore marine clastics pinch out basinward (westward), at or near the position where the underlying sandstone obtains maximum thickness. In general they thicken shelfward (eastward). Immediately overlying the varicolored clastics above the Red Valley and Second sand is a thin zone of conglomeratic sandstone, containing marine fossils, which grades into the main reservoir along the basinward edge of pay zones where the varicolored clastics are missing. Absence of good separation between the pay sand and the thin conglomeratic sandstone has led to the interpretation that the pays are characterized by a cap rock of conglomerate (Dickey, and others, 1943, p. 31). Actually the "Cap Rock", included in past total sandstone isopachs, is a separate sandstone of somewhat different origin than the pay sandstone.

Maximum thickness of the reservoir zones occurs along the basinward edge of the deposits. Rapid gradation of the reservoir zones into dark gray to black marine siltstones and shales occurs to the west. A gradual decrease in thickness and change in facies to a more continental sediment occurs to the east. The continental facies includes lenses of conglomeratic sandstone, sandy siltstone, and silty shales, in part varicolored.

### REGRESSIVE-TRANSGRESSIVE ALTERNATIONS

Assuming that the varicolored intervals represent continental deposits, and that the dark marine shales represent basinal marine deposits, it is possible to get some idea of the relationship of the reservoir zones in time. Figure 3 illustrates diagrammatically the transgressive-regressive alternation of marine conditions during deposition of the upper part of the Venango sequence modified after Dickey and others, (1943, p. 34-39).

The distribution and relationship of the main pay sands indicate deposition during marine regressive phases, with maximum development of thickness just prior to maximum regression. Clastic deposition during the marine transgressive phases is limited to the thin, conglomeratic sandstones overlying the varicolored intervals. There is a lack of appreciable reservoir development in these largely discontinuous sandstones indicating 1) that the supply of continentally derived clastics from the east diminished at the end of marine regression as erosional base leveling of source highlands was completed, 2) rapid marine transgression over a submerged shoreline, or 3) a combination of these events. Maximum supply of clastics and/or stability of shoreline appears to be represented by the development of the important reservoir zones.

The Red Valley sandstone is one of the more widespread and prominent pay zones of the Venango sand sequence. Further examination of this sandstone defines a general stratigraphic and petrographic pattern applicable in principle, if not in detail, to the other major zones of the sequence.

## RED VALLEY ECONOMIC RESERVOIR FACIES

The distribution of reservoir zones in time and space, although important, lacks economic significance. Not all reservoir zones are economically profitable. Some produce noncommercial fluids, and others although productive, are not profitable. It is necessary to determine those reservoir beds, or portions of reservoirs, capable of delivery of profitable quantities of oil and/or gas. For purposes of this discussion, important economic considerations in establishing productive reservoir limits in the Red Valley other than geological will be omitted.

### VENANGO STRATIGRAPHIC TRAPS

Pay zones in the Venango sand sequence are essentially the result of the occurrence of stratigraphic traps, with structure playing a minor role (Sherrill and others, 1941; Dickey and others, 1943). Consequently, permeability to hydrocarbons entrapped within the reservoir zone becomes a critical factor in recovery if adequate reservoir pressure is present and/or

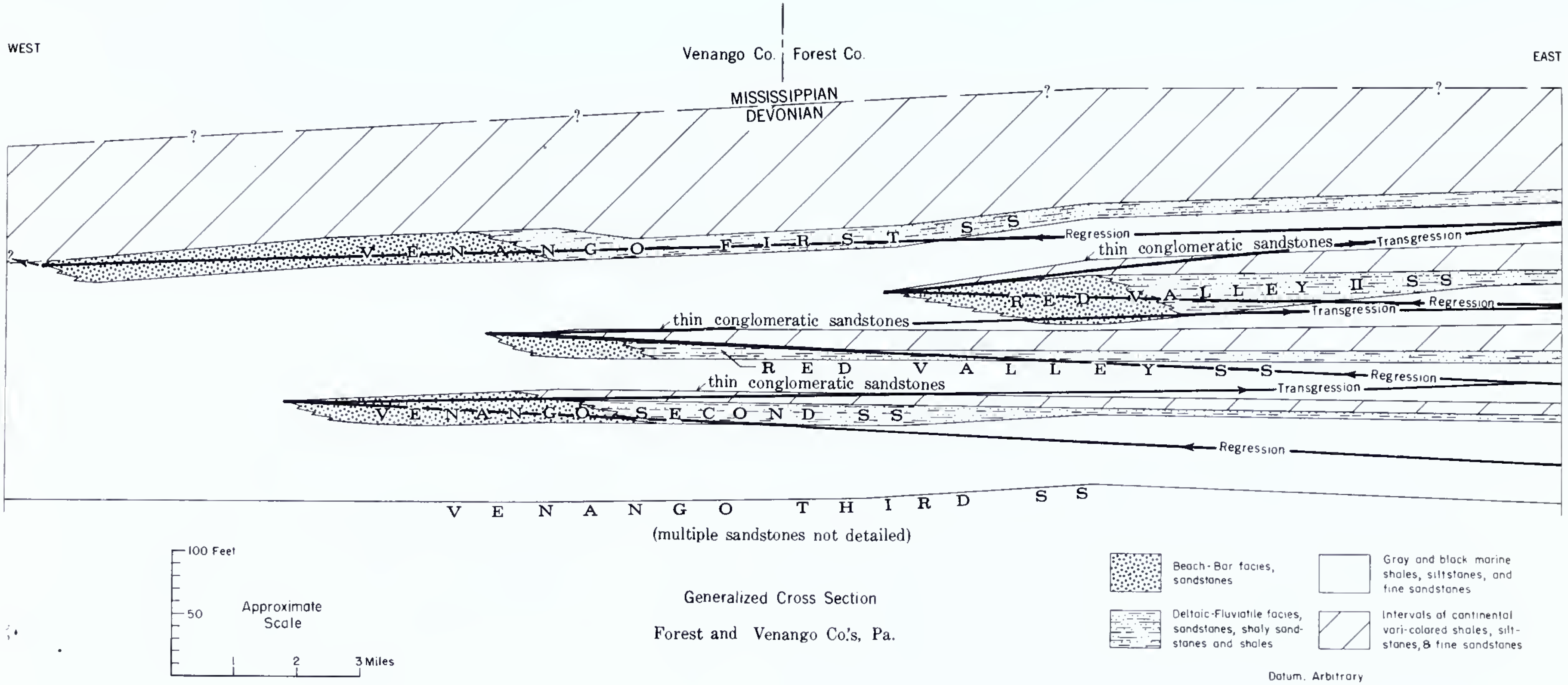
WEST
Venango Co.
Forest Co.
EAST
MISSISSIPPIAN
DEVONIAN
?
VENANGO FIRST SS
Regression
Transgression
thin conglomeratic sandstones
RED VALLEY II SS
Transgression
Regression
thin conglomeratic sandstones
RED VALLEY SS
Regression
thin conglomeratic sandstones
Transgression
VENANGO SECOND SS
Regression
VENANGO THIRD SS
(multiple sandstones not detailed)
100 Feet
50
Approximate Scale
1
2
3 Miles
Generalized Cross Section
Forest and Venango Co.'s, Pa.
Beach-Bar facies, sandstones
Deltaic-Fluviatile facies, sandstones, shaly sandstones and shales
Gray and black marine shales, siltstones, and fine sandstones
Intervals of continental vari-colored shales, siltstones, & fine sandstones
Datum, Arbitrary

Figure 3. Transgressive-regressive relationships of the upper Venango sandstone sequence.

has been maintained, and if the formation has not been damaged by previous detrimental operations within or adjacent to the area of interest.

Increased molecular energy and/or decreased molecular size enables water and gas to be transmitted through lower permeability conditions than for oil. Consequently, parameters used in establishing productive reservoir limits for gas production will differ from that of oil production from the same horizon, other factors being equal. In the oil-producing Red Valley sandstone it was necessary to establish the minimum permeability, below which it would be most difficult to recover oil in commercial quantities, and a permeability value above which considerably profitable quantities of oil could be reasonably anticipated. Transferability of the entrapped oil, which is dependent upon reservoir permeability, is essential to profitable production. Regardless of the primary or secondary recovery or stimulation technique, there is a limit to which the mechanical propagation of permeability, such as by hydrofracture and acidizing, will be effective. No matter how many channels for transfer of fluids are produced by these methods, if the rock cannot give up its hydrocarbons to the induced channels, recovery techniques are ineffective, or at best result in a nonprofitable, rapidly declining, marginal producer. In these cases the only oil that is recovered comes from the rock immediately bounding the induced channels.

## ECONOMIC LIMITS FOR PERMEABILITY PINCHOUTS IN THE RED VALLEY

Except in a few cored wells, permeability determinations can only be inferred. However, in nearly all stratigraphic reservoirs there is a reasonably direct relationship between porosity, which can be derived from mechanical logs, and permeability. Figure 4 illustrates this relationship in the Red Valley. The upper portion of the curve is not well established. Available analysis of high porosity-high permeability zones are limited.

Utilizing accurate production data in comparably hydrofractured, average wells, it is possible to establish a usable direct relationship between porosity, thickness, and productive capability. Reasonably reliable production information has been received for eight recent wells located just to the east of the area of old prolific Red Valley production in the Petroleum Center-Pioneer-Pleasantville-Shamburg field trend. The data is from wells which are primary open hole, hydrofractured, pumping completions. The wells are located outside of the optimum reservoir development and near old fields, which are in part fresh water invaded. The data from these wells show increased production with increased net

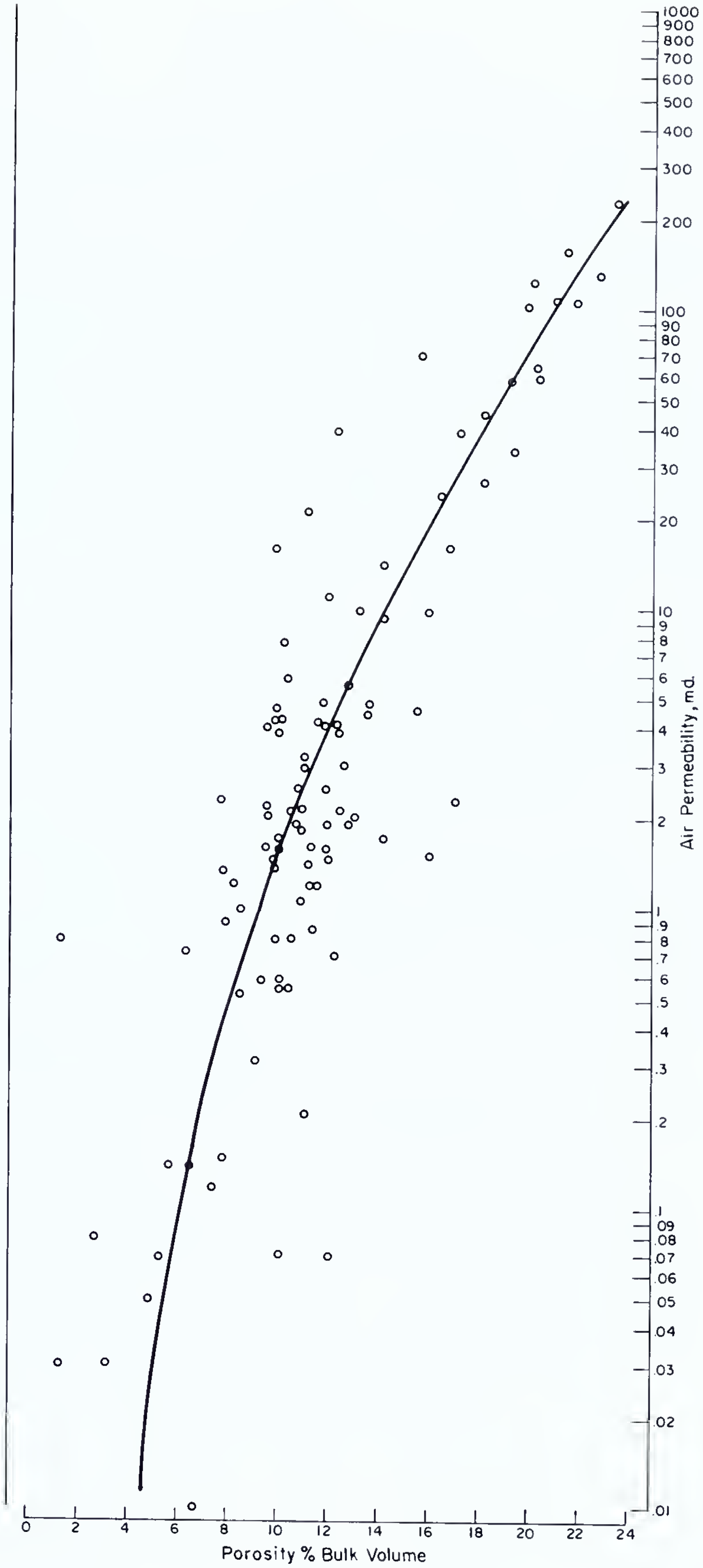

Figure 4. Porosity-permeability relation in the Red Valley Sandstone of Venango County, Pa., based on five analyzed wells.

pay, as indicated in Figure 5. A similar direct relation can be shown using variously weighted mathematical combinations of percent porosity and net pay plotted against production. Utilizing these data together with reports of initial potentials in logged and cored wells, it is believed that at this time approximately 5 feet or more of 10 percent porosity or better, or 2 feet or more of 12 percent porosity or better, is the lower economic limit for production in the Red Valley. This limit would represent a pumping, open hole, hydrofractured, well averaging 5 BOPD (Barrels of Oil Per Day) with pay out in a year. A limit of one foot or more of 20 percent porosity or better reasonably includes the zone of prolific production in the Red Valley of the old Petroleum Center-Pioneer-Pleasantville-Shamburg field trend, and is tentatively used to define optimum productive, porous reservoir conditions. Therefore, limits that define the

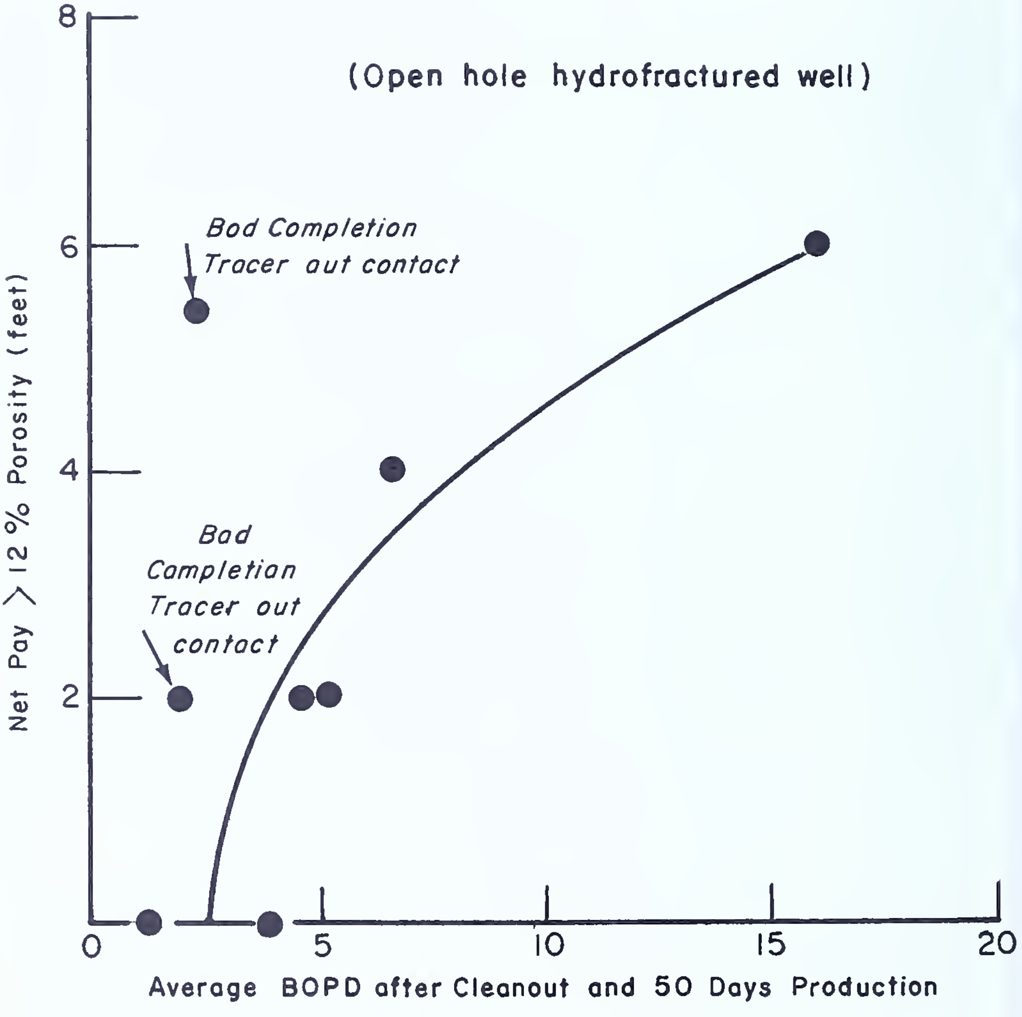

Figure 5. Porosity and production in the Red Valley Sandstone.

economic reservoir facies are: the profitable reservoir facies of plus 1 foot of 20 percent porosity or better, the marginally productive reservoir facies of plus 5 feet of 10 percent porosity or better to the lower limit of the profitable reservoir facies, and the nonproductive reservoir facies (at this time) being less than 5 feet of less than 10 percent porosity.

Attempts to arrive at more precise relationships between porosity, net pay and production, or reserves, are limited by the availability of reliable information. Erratic or ineffective completion methods, effect of fresh water invasion, and depleted reservoir pressures in and bounding the many old fields in the area must be considered in establishing these relationships. Past reserve and production estimates, such as are presented for example in "Crude Oil Reserves of Pennsylvania" (Lytle, 1950), lump marginal and profitable areas together, and cannot be used. However, taking all factors into consideration the profitable reservoir facies includes areas in which 1) wells drilled in the late 1800's frequently came in flowing in excess of 200 BOPD, 2) analyses of cores showed permeabilities in the hundreds of millidarcies (md), 3) net pays were generally in excess of 10 feet, and 4) reserve estimates of 5000 to 6000 barrels per acre or better were made. The marginal reservoir facies was frequently bypassed for completion attempts in early drilling. Unlike the profitable facies, natural shows of free oil during drilling were seldom encountered, and present initial completions are pumping at generally less than 50 BOPD. Permeabilities greater than 15 millidarcies and net pays in excess of 10 feet rarely occur in this facies. Reserve estimates in the better portion of this facies are in the range of 3000 to 4000 barrels per acre or less.

## MAPPING ECONOMIC RESERVOIR FACIES IN THE RED VALLEY

In order to delineate the spatial distribution of the established economic facies of the Red Valley it is necessary to gain an understanding of the mechanism of formation of the reservoir, and the relation of the overall reservoir zone to the economic facies. Are the reservoir deposits associated with, or caused by, ancient fluviatile channels, beaches, bars, deltas, turbidity currents, all having different forms of accumulation? Except in areas densely drilled with good log control, some knowledge of the genesis of the reservoir is essential in establishing the pattern to be interpreted by projection from scattered well control. Attention to basic geology can materially contribute to profitable exploration for and exploitation of well locations. In addition, geology is an important aid in the selection of secondary recovery patterns in a field lacking good modern log control.

A nearshore beach and bar origin and depositional pattern for the Venango sand sequence is indicated (Dickey, and others, 1943, p. 32; Dickey 1941, p. 13; Sherrill and others, 1941). The petrology of the productive sands, shape of the sand bodies, and the geological setting all point to this origin. By preparing isopach maps of 80 percent or better gamma-ray clean sand it is possible to illustrate the distribution of the Red Valley reservoir (Plate 2). The sandstone, sufficiently shale free to possess minimum porosity necessary for production, records on gamma-ray logs as 80 percent or better. The technique is similar to that used in mapping Medina gas productive trends (Kelley, 1966, p. 34-36). The greater than 10 feet of 80 percent or better gamma-ray clean sand essentially outlines the ancient beach deposit, now characterized by Red Valley maximum thickness development. A total Red Valley sand thickness isopach would extend from just a little west of the clean sand zero line in Venango County to east of the mapped area, and would not reflect reservoir distribution as well as the gamma-ray isopach does. Increased clean-sand thickness generally corresponds with increased total sand thickness. However the proportion of the total sand thickness that is gamma ray clean may vary widely in local areas. Present data indicates a range from 36 to 72 percent of the total sand thickness may be 80 percent clean, accounting for considerable local disparity between total and clean sand trends. Isopachs utilizing drillers logs and scout tops include the overlying varicolored clastics and. the thin transgressive conglomeratic sandstone in much of the western portion of Forest County. These poorly reflect sand distribution of the Red Valley reservoir. The asymmetrical clean sand thickness maximum occurs along the west edge of the northeast-southwest trending overall deposit of clean sandstone. Rapid basinal thinning and gradual shelfward thinning of the gamma-ray clean sand is characteristic (Plate 2).

The distribution of economic facies, shaded in Plate 2, is important. The position of maximum clean sandstone does not represent the optimum porous reservoir which is located along the basinal flank, possibly related to the effect of seaward winnowing of fines from the coarser clastics during deposition. A reasonable relationship exists between the marginally productive reservoir and the eastern shelfward limit of the beach deposit as defined by the 10-foot clean sand isopach. Clean sandstone embayments and irregularities along the eastern flank of the deposit may represent deltaic or fluviatile influences and point to areas in which future detailed investigations could reveal profitable east-west local cross trends. In addition, the southwest projecting isopach thinning across the Venango-Forest County line could have pre-Red Valley exploratory structural and/or stratigraphic significance.

Attention is directed to the fact that Plate 2 is a regional interpretation utilizing available but widely scattered mechanical log well control. It adequately illustrates the general pattern and distribution of the reservoir zone and economic facies to be expected. However, the distribution of the clean sand trend and economic facies is not likely to be as continuous and uninterrupted as shown. In the southern portion of the map, where there is maximum log control, irregularities are apparent in the clean sand isopach. These are lacking to the north where control is sparse. Additional data would undoubtedly allow refinement in delineating and mapping the Red Valley reservoir. It would also point to areas of discontinuous reservoir development, areas of significant widespread reservoir development, and areas of shelf cross trends and embayments important in programming exploration, exploitation, and secondary recovery operations.

Other benefits derived from this type of geological mapping can be accomplished by more detail. Establishment of net pay and porosity gradients would be of considerable use in determining development and secondary well spacing. Similar definition of economic facies for other major producing intervals in the Venango sand sequence would allow prediction of profitable multipay prospects and extensions. The regressive-transgressive pattern exhibited by Figure 2 is not areally consistent. Periods of differential subsidence and uplift in time, in different portions of the Appalachian basin, as well as the effect of supratenuous folding on subsequent deposition, could have produced local disruptions and change in sedimentary strike resulting in crossing and divergence of reservoir sand trends.

## RED VALLEY STRUCTURE

Surface and shallow subsurface structure over much of the western plateau of Pennsylvania is characterized by gentle southerly regional dip. Plate 2 illustrates regional structure on the top of the Red Valley sandstone, or its equivalent, within the subject area.

A relatively weak southwest plunging nose (flexure) is roughly coincident with the Red Valley reservoir sandstone trend. Structures that are generally coincident with reservoir sand developments have been demonstrated elsewhere in the shallow Upper Devonian; for example on top of the Speechley sandstone (Dickey and others, 1943, Plate VII), and on top of the Glade sandstone (Linn, 1965, Figure 1). Analyses of the relationship of structure and sandstone deposits in Pennsylvania have not been adequately discussed in the literature. Incomplete evidence suggests that in some areas the structural anomalies represent supratenuous folds (compaction folds over resistant sandstone masses). In the subject area there is not enough detailed control to demonstrate the origin of the Red Valley nose. Structure maps prepared on the base of the Red Valley sandstone indicate the presence of a similar southwestward plunging feature, suggesting that the nose is not entirely of sedimentary origin, because the basal contact is similarly warped.

Some attention should be directed toward investigation of these features. The understanding and delineation of supratenuous folds, particularly if revealed in the surface and shallow subsurface sections, could be of considerable aide in defining underlying reservoir distribution. On the other hand, the understanding and definition of nondepositional structures could point to areas of the basin edge, along which sands were preferentially deposited, and along which later structural adjustments preferentially occurred. These could also generally reflect deep seated features which may have significance in the localization of hydrocarbon traps in pre-Devonian sediments.

The influence of structure on production appears to be, at best, minor in this area of the Red Valley. Production did, and does, occur primarily related to reservoir development. It is possible that areas of discontinuous sand deposition along strike could form updip migratory barriers with partial fluid segregation in adjoining thick and porous reservoir lenses. The absence of available or reliable water cut and GOR (Gas-Oil Ratio) information for production prohibits resolution of this question. It is interesting to note that Red Valley fields in the Oil City quadrangle, structurally lower than the mapped area, have significant water cuts (Dickey and others, 1943, p. 89). In the northern portion of the Tidioute quadrangle Ashley (1938, p. 8 and Figure 5) noted the presence of small amounts of water and locally significant amounts of gas. Again, this represents another field of study where additional information and investigation could produce practical results. More data on produced fluids could significantly implement an understanding of the mechanism of hydrocarbon migration and entrapment. Anomalously high connate water cuts in scattered wells in underdeveloped areas could point to significant reservoir deposits where segregation of fluids was possible and major hydrocarbon accumulations could be anticipated updip.

## FAULTS AND JOINTS

The effect of primary faulting and jointing on the productive capability of the Red Valley reservoir does not appear to be important. The Red Valley is excellently jointed where exposed. Also, faulting and jointing of exposed overlying Mississippian rocks at the surface is common. The faults generally strike northeast. The various joint sets have not been analyzed. All fractures are essentially vertical or near vertical. Occasional cores reveal vertical lineations, which on examination, appear to be minute, discontinuous, well-cemented joints. Rarely are these incipient fractures open to any extent. The few open fractures seen in core pieces may have resulted from the percussive effect of drilling. Occasionally, detrital minerals are minutely "fractured" in thin sections. However, these "fractures" are well cemented with silica or carbonate (Plate 5, Figure 4).

The excellent relationship between productive capability and sedimentary parameters mitigates against jointing and fracturing playing a significant primary role in reservoir quality or capability. However, these features may represent relative planes of weakness which, with hydrofracture treatment, are opened to produce vertical channels for hydrocarbon migration from the oil-bearing reservoir. Further evaluation of fractures is warranted. The distribution of these incipient vertical channels may be important in programming effective hydrofracture treatments.

## PETROGRAPHY OF THE RED VALLEY SANDSTONE

Considerations of the petrography of the pay zone can 1) materially refine the understanding of the genesis of the distribution of the reservoir, and consequently aid the accuracy of projection of profitable trends and 2) determine proper completion and recovery operations which will insure maximum return of hydrocarbons. It will also contribute to the decreased possibility of damage to the formation which could detrimentally effect the application of future secondary and tertiary recovery methods. It is only after satisfactory primary completion methods have been applied that appropriate flooding operations can be successful. Many secondary recovery projects have been accomplished in areas where primary treatments have done little, if anything, to prepare the rock for flooding operations, particularly in the marginally productive facies. If significant carbonate cement has not been reduced, if damage by swelling clays has formed unsuspected impermeable blocks, or if transferable fine-sized clay particles have plugged permeability capillaries, the secondary treatment cannot be expected to be successful. It is suspected that many secondary recovery methods have been discarded because primary preparation of the rock was ineffective, not because of the method. More attention to rock components and their distribution is required and more practical petrology is necessary.

A preliminary petrographic and mineralogical examination of the Red

Valley sandstone was made from 12 different wells in which samples were available. The numerical sampling control for this examination is tabulated in Table 2. General areas of sample selection are shown on Plate 2.

In the Venango sand sequence, including the Red Valley sandstone, whole core, Baker Core, and chip core samples are extremely rare. Cable-tool samples are not readily available considering the number of wells being drilled. In fact, there is little evidence that those few samples that are caught and saved are adequately evaluated by standard well site geological descriptive methods. Fortunately enough material was obtained to afford some indication of gross petrographic and mineralogic variations regionally and within a producing field. These variations form a reasonably logical pattern in context with the interpreted depositional history and indicated postdepositional changes. Further investigation of additional sample material should afford the verification and details necessary for important practical application.

No attempt will be made to present a comprehensive petrographic analysis, comparable to P. D. Krynine's "Petrology and Genesis of the Third Bradford Sand" (1940). The control is not adequate for this type of analysis. The purpose of the preliminary investigation is to appraise factors that are believed to exert a major influence on productivity of the Red Valley sandstone, whether these factors are variable and occur in a reasonably predictable pattern, and whether certain of these factors warrant additional investigation. Although some petrographic data pertinent to the Venango sand sequence are available in the literature (a few random examples being Fettke, 1927; Fettke, 1928; Dickey, 1941, p. 16-21; Modarresi and Griffiths, 1963), the data are not presented in spatial context. It is not known whether the analyzed wells or fields are typical or atypical for production from the pay zone or what variations in parameters occur between highly productive, marginally productive, nonproductive or problem wells. An understanding of variability not only in section but also in plan, is necessary before optimum applicability of petrographic data can be anticipated.

## GENERAL DESCRIPTION OF THE RED VALLEY SANDSTONE

The mineralogical composition of a typical fine-grained pay zone in a well located along the western limit of the marginally productive facies of the area is shown in Table 3. These data are derived from microscopic, grain size, solubility, and X-ray diffractometer analyses. Minor secondary alteration products and stains are not considered.

Significant variations in the composition and grain size occur vertically above and below the pay zone, and horizontally within the pay zone.

Table 2. *Sample Control (Number of different wells examined where samples were available.)*

| | Binocular microscope, and some stain tests | Petrographic microscopic (Thin sections) | X-ray diffraction of "Fines" | Grain-size analyses and some acid solubility tests | Chemical analyses |
|---|---|---|---|---|---|
| Basin equivalent | | | | | |
| Silts and shales | 1 | | 1 | | |
| *Profitable facies | | | | | |
| Pay | 2 | 1 | | 1 | |
| Other lithologies | 1 | 1 | | 1 | 3 |
| **Marginal facies | | | | | |
| Pay | 8 | 1 | 2 | 4 | |
| Other lithologies | 8 | 1 | 2 | 2 | |
| Nonproductive facies | | | | | |
| Pay equivalent | 1 | 1 | 1 | 1 | |
| Other lithologies | 1 | | | | |

* Includes one chip core well
Other wells were cable tool sampled
** Includes two Baker cored wells

Table 3. *Average mineral composition of a productive Red Valley sandstone.*

| | | |
|---|---|---|
| Detrital minerals (Microscopically distinguishable) | | 85-90% |
| Detrital minerals are generally subrounded to subangular, having low to moderate sphericity. | | |
| Quartz, various types | 69-82% | |
| Feldspar, minor potash, mostly albite to andesine | 5-10% | |
| Muscovite flakes (rarely biotite) | 1-2% | |
| Rock fragments | 1-2% | |
| Heavy minerals and accessory minerals | 1-2% | |
| Detrital and/or cement (Microscopically indistinguishable) | | 7-9% |
| Silica (secondary and/or primary, chalcedony-quartz?) | 7-9% | |
| Feldspar (detrital) | Tr-1% | |
| Cement (Determined by X-ray) | | 3-6% |
| Kaolinite | 1-2% | |
| Illite | ½-1% | |
| Possible Chlorite | Tr-1% | |
| Ankerite | 1-2% | |
| Total | | 100% |

## GRAIN-SIZE DISTRIBUTION

The Red Valley sandstone is predominantly a very fine-grained sandstone, but occasionally ranges to pebbly conglomerates or granulites. Selected grain-size analyses were made of available samples of the pay zones in wells located in the profitable, marginal, and shelf facies, and of the upper and lower nonproducing portion of the Red Valley sandstone in the marginal facies.

The generally well-cemented, fine-grained sandstones of the Appalachian Basin are not adaptable to accurate grain-size analysis by standard methods, because nondestructive disaggregation is a severe problem (Krumbein & Pettijohn, 1938, Chapter 3). Investigation of recently developed sonic disaggregation and automatic thin section photographic methods of grain-size analysis is in progress.

In this preliminary survey of the Red Valley sandstone, destructive methods were avoided and attempts were made to preserve all rock components. Chemical pretreatments before crushing, used by Fettke (1927, p. 4), were not employed. Baker core samples were reduced to approximately one-quarter inch pieces mechanically or by hand. These samples, and the similar sized hand-picked chip core and cable tool samples, were subsequently carefully hand disaggregated by tapping in a porcelain mortar and pestle with frequent microscopic evaluation to avoid excessive artificial intragrain crushing, and to determine the effectiveness of disaggregation. U. S. Standard sieve screens were used down to 325 mesh (.043 mm) and standard elutriation procedures utilizing ammonium hydroxide as a dispersant were used to obtain the range of grain-size classes (Figures 6 and 7). In an attempt to make results comparable, the quantity of sample used in analysis was restricted to a range of between 7 and 15 grams, the amount of sample normally obtainable from cable tool wells by hand picking. Various tests were made to check validity of results by testing for reproducibility. Artificial crushing of grains was limited to approximately 7 to 10 percent of the total sample by weight as determined by visual estimate. In order to keep this figure reasonably low, 12 to 21 percent of the total sample by weight was not disaggregated. The proportion of the fine aggregate pieces, distributed mostly in the larger size classes, was microscopically estimated in the screens in which they were caught and eliminated from consideration. Reproducibility on the same samples reanalyzed and different samples of the same zone, was between 8 to 10 percent of the total by weight, a minor amount considering that this proportion was distributed in a number of classes. Procedural loss of material was 6 to 8 percent of the total by weight, only 3 to 5 percent in the screened portion (mostly material caught in screens), and held to less than 25 percent of the small amount elutriated (liquid transfer and filtration).

Grain-size analyses of the well-cemented Upper Devonian sandstones are at best approximate. Fine-grained mixtures of interstitial clays, carbonates, quartz, and detrital particles form a tightly interlocking texture difficult to cleanly separate without altering the components. Secondary quartz overgrowths and corrosion of detrital particles by carbonates distort to some extent the original grain shape and size. Consequently, the best separation of mineral components will, on analysis, result in a postdepositionally modified grain-size distribution. However despite some error resulting from procedure and type of sediment being studied, grain-size analyses afford useful data in interpreting sedimentary history and petrography.

### Well-Sorted Pay Zones

Figure 6 illustrates the results of screen analyses of typical pay, silty, and coarse intervals of a few of the other prominent reservoir zones of the Venango sand sequence within the area of study. Figure 7 shows the

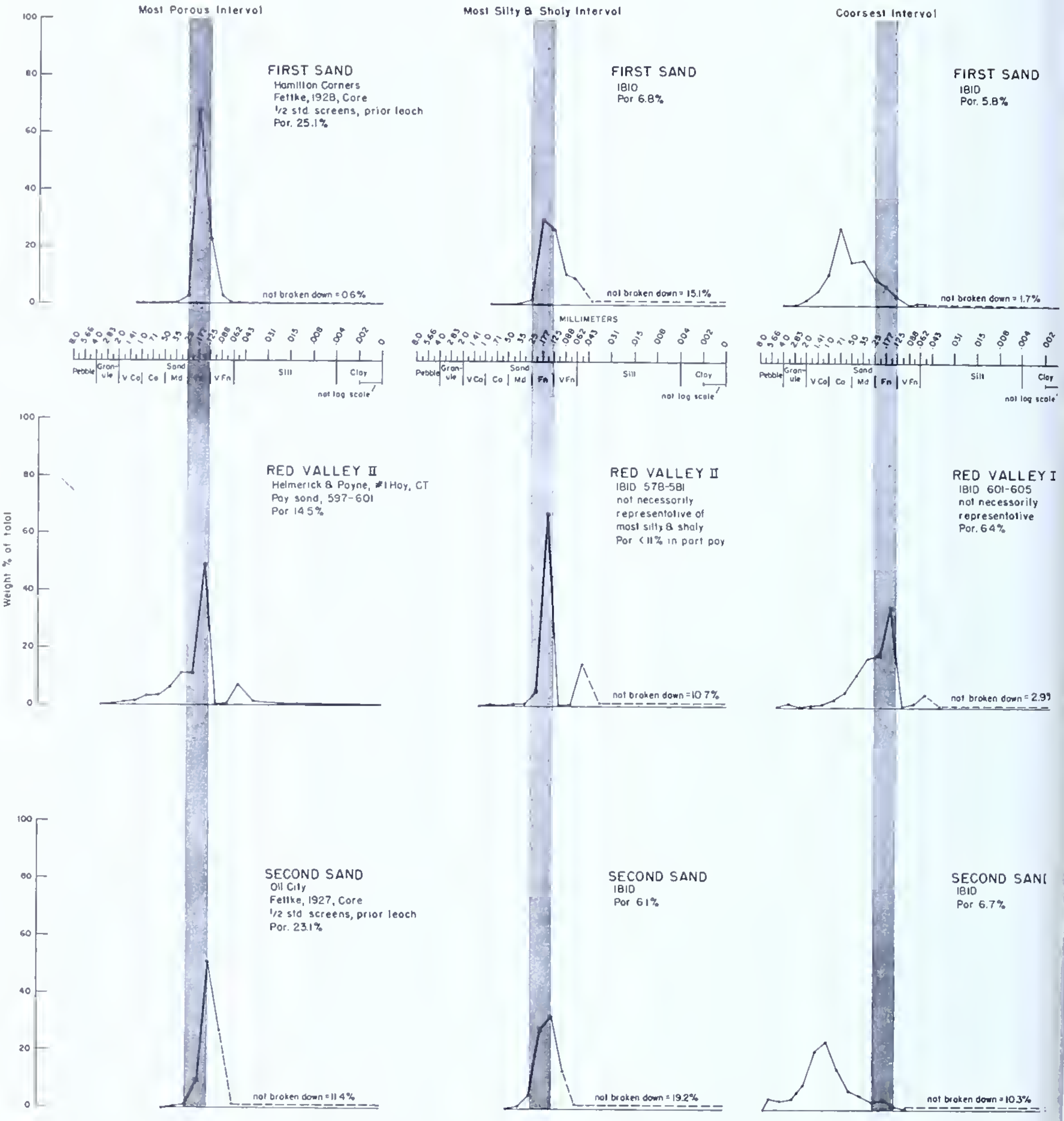

Figure 6. Frequency curves of grain size distribution of some Venango sandstones.

results of some grain-size analyses of the Red Valley sequence arranged spatially, though not to horizontal scale. The well-sorted character and limited amounts of clay and silt size particles in the fine to very fine sandstone pay zones is evident. There is a remarkable similarity in the modal class for the various fine-grained pay zones of the different sands. Nonproducing intervals of the productive sandstones also are generally fine grained, fairly well sorted, and have a limited size range. The variation in sorting across the economic facies is illustrated in Figure 7. From the profitable facies pay zone, represented by the Wolf's Head No. 78A

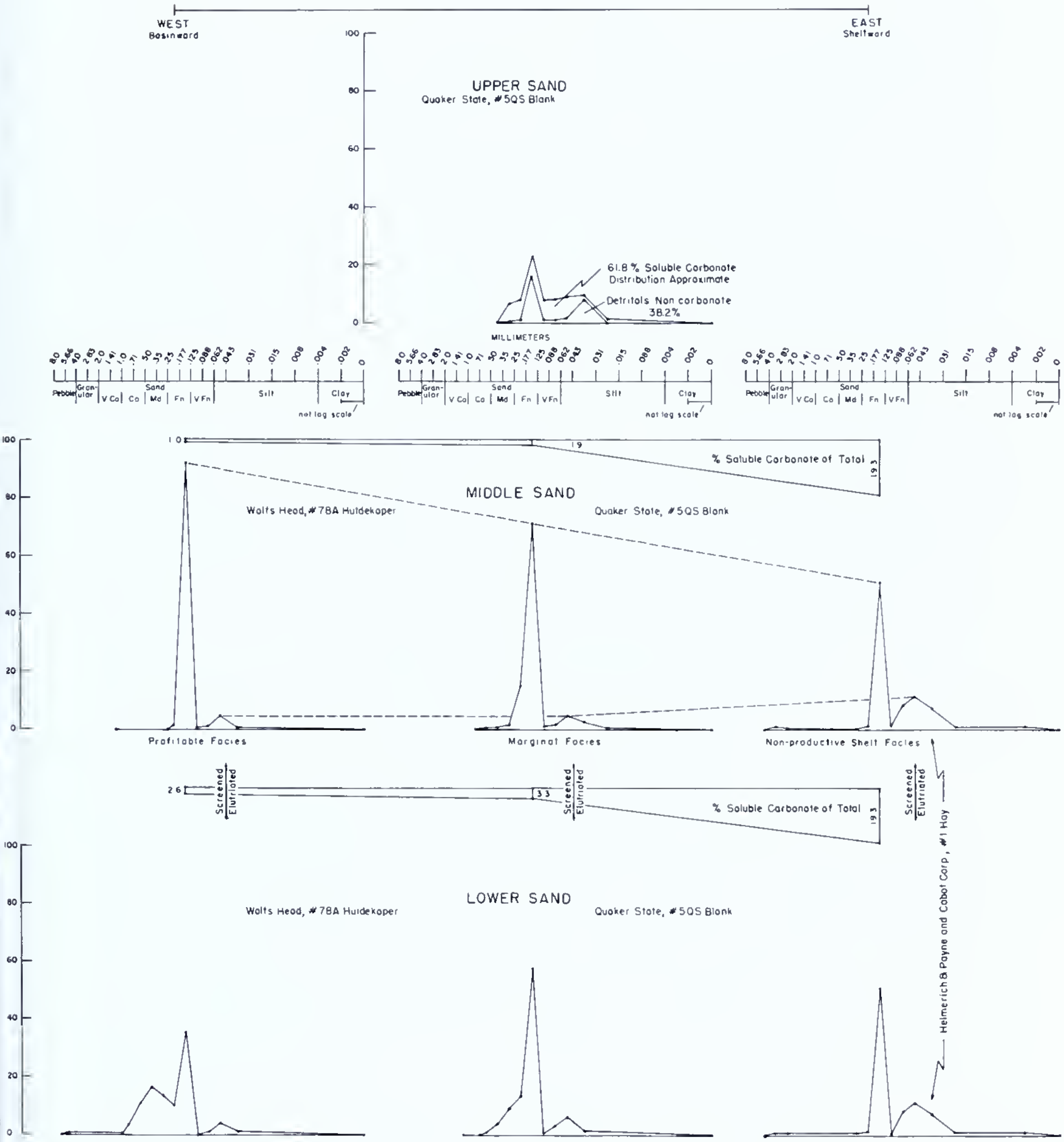

Figure 7. Frequency curves of grain size distribution of some Red Valley sandstones.

Huidekoper middle sand analysis, to the marginal facies pay zone, represented by the Quaker State, No. 5Q S. Blank middle sand analysis, to the thin nonproductive sand of the Helmerick and others, No. 1 Hay, there is a decrease in grain frequency in the modal class accompanied by an increase in submodal fines. This change is particularly significant between the marginal facies and nonproductive shelf facies, where the total range in grain-size distribution increases also. A similar increase in amount of fines is noticeable for the lower sand, although this part of the Red Valley becomes coarser basinward. Photomicrographs in Plate 4 illustrate some of the variations in grain size among the various facies. The upper part of the Red Valley grades downward from a sandy and silty carbonate at the top to a carbonate-cemented fine, silty sandstone near the top of pay. The grain-size distribution can be noted in Figure 7. The carbonate distribution is approximate, since it is based largely on microscopic analysis and solubility of some size fractions.

Where the sands are productive of oil, the composition, sorting, limited size range, and few species of heavy minerals, exhibit the characteristics of beachbar depositional history as noted by Dickey, and others (1943, p. 31-33). This lends support to the map interpretation of a linear shoreline trend for the reservoir deposits. The petrography contrasts sharply with that of the more poorly sorted Third Bradford sandstone in the Bradford field, which is a medium-to fine-grained graywacke with comparably abundant rock fragments and accessory and heavy minerals. The Third Bradford sandstone was deposited primarily in a deltaic environment (Krynine, 1940). Map interpretations of reservoir thickness and economic facies of the Third Bradford sandstones can be expected to be dissimilar to that of the Red Valley sandstone.

Figure 8 illustrates, from limited available Red Valley data, the general relationship of increased porosity accompanied by increased concentration of detrital grains in a particular grain-size class (modal class). The relationship of the more porous sands with increased uniformity in grain size (or sorting) is well established (Fettke, 1928, p. 8; Headlee and others, 1957, p. 22). Figure 9 shows the same data relating porosity to the coefficient of sorting. However, in this figure the analyses of quartile distributions of grain sizes is less sensitive to differentiation of marginally productive sandstones from the profitable sandstones than by using percent sizing in modal class. Figure 10, relating pore-plugging fines and cement to porosity indicates the possible effect that a small change in amount of fines and cement may have on porosity. In the relatively "tight" Venango sands, the limited data suggests that fines and cement between 10 and 25 percent may be sufficient to prohibit commercial production under present reservoir conditions and primary completion methods. Less than 5 percent pore-plugging fines and cement may allow sufficient porosity and permeability to afford a highly profitable well, other factors being equal. A relationship of decreasing permeability with increasing amounts of interstitial fine material was brought out by Headlee and others (1957, Figure 3, p. 22) for the Maxton and Big Injun sandstones. Relationships between porosity and other statistical grain-size parameters, such as sizing coarser than modal class, skewness, and kurtosis, are not clear. It is evident that the cleaner, better-sorted sandstones make pay zones; the more sorted and free of pore-plugging fines,.

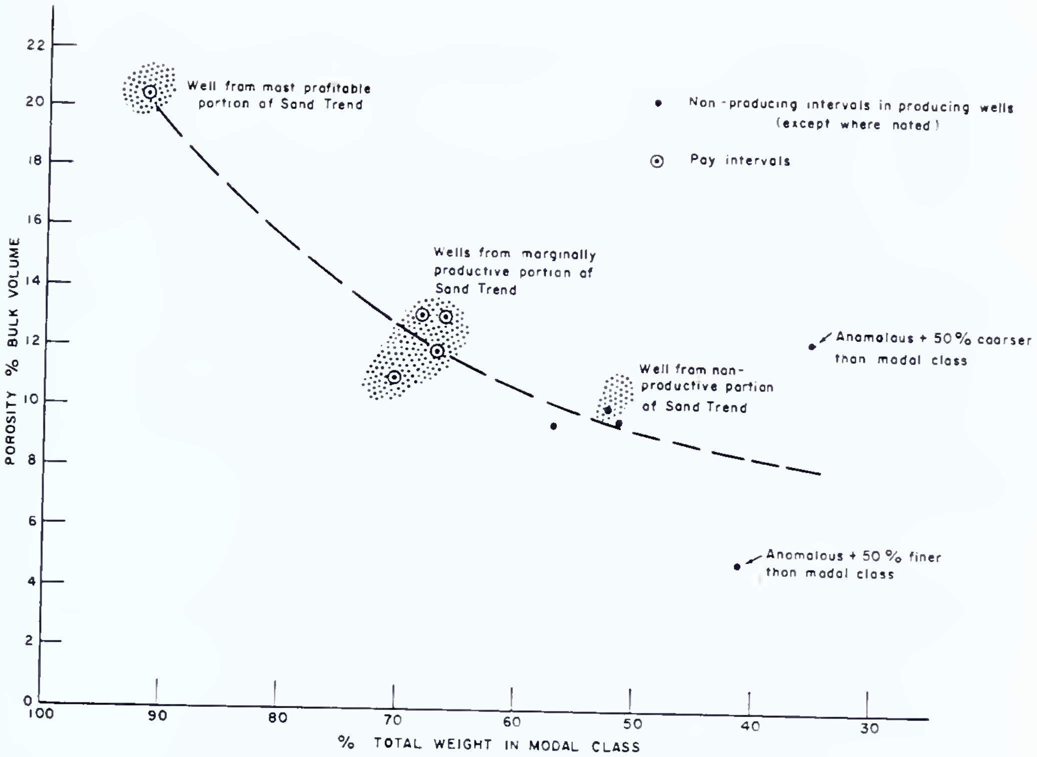

Figure 8. Relation of porosity and restricted grain sizing in the Red Valley Sandstone of Venango County.

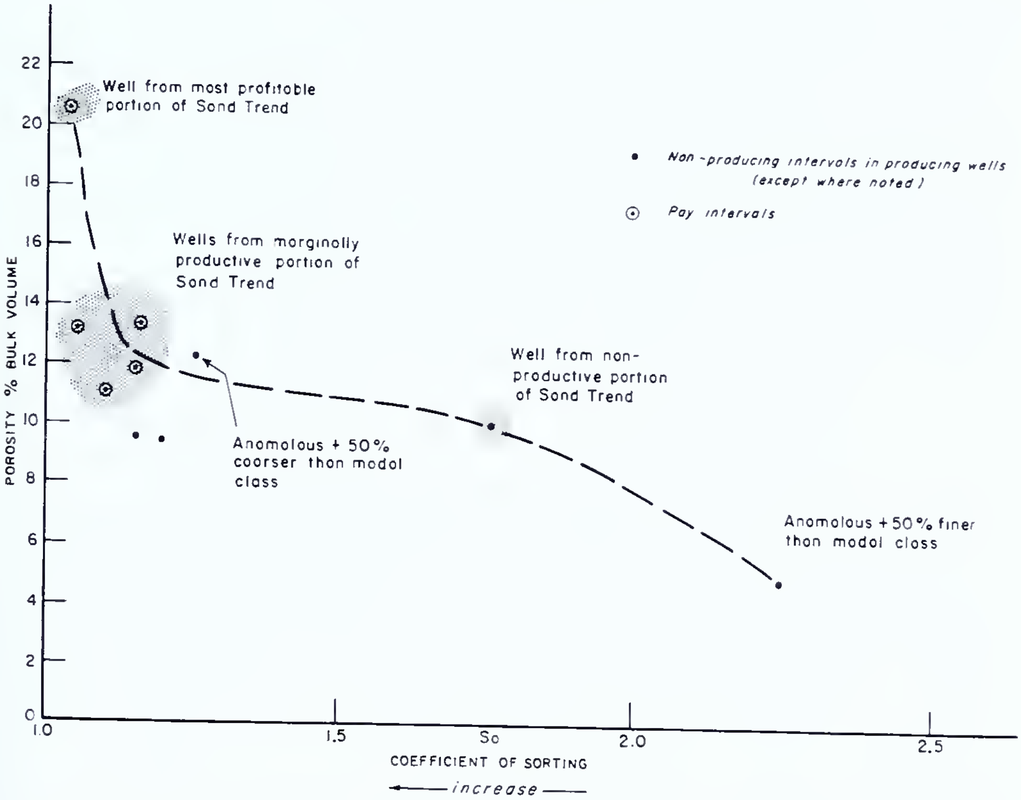

Figure 9. Relation of porosity and grain size sorting in the Red Valley Sandstone of Venango County.

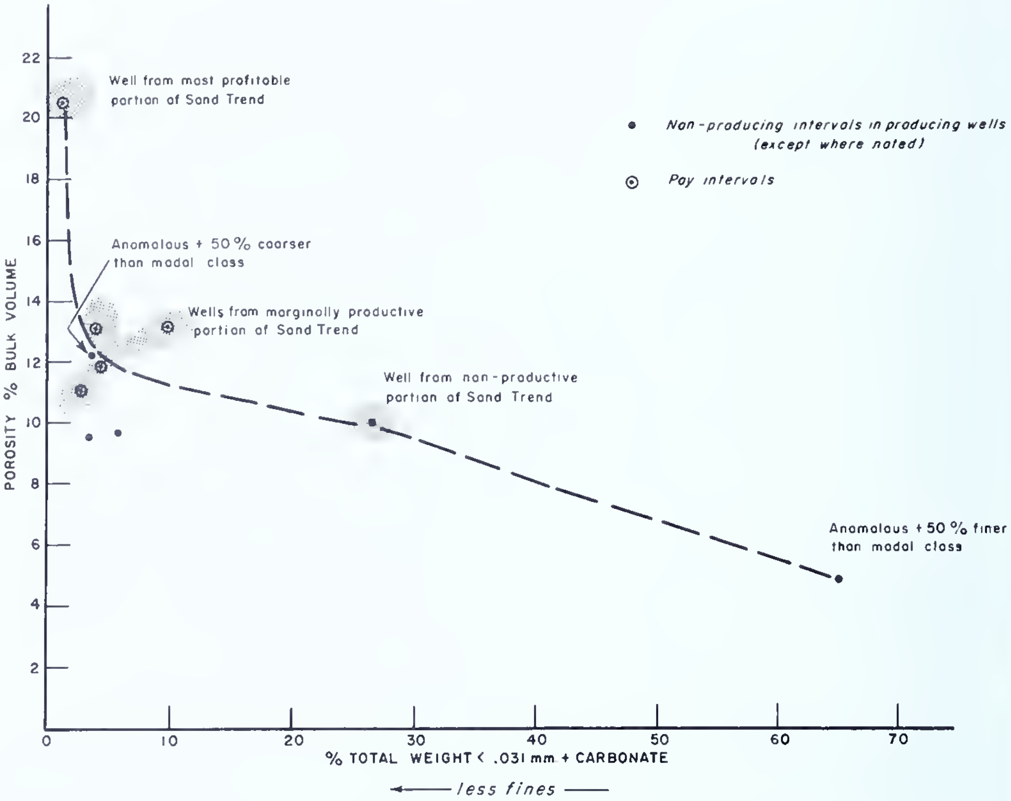

Figure 10. Relation of porosity and "fines" and cement in the Red Valley Sandstone of Venango County.

the more porous the sandstone will be. The restricted distribution of the profitable economic facies can be assigned to the limited portion of the sedimentary environment in which the detrital grains were cleaned of pore-plugging fines through winnowing action. The broader marginally productive trend represents the bulk of the beach deposits located back of the maximum effect of continuous wave and current action.

## PORE-PLUGGING FINES AND CEMENT

Assuming that an average grain size of the modal class of a well-sorted pay zone is between .177 and .125 mm and that there is hexagonal close packing of spherical grains, then silt and clay sized particles and cement of approximately .03 mm and less could be expected to fill available voids and constitute the significant interstitial pore-plugging fine fraction. Natural variations in sorting, roundness, sphericity, packing, and texture however restrict the above definition of pore-plugging fines such that it should be used only as a model having certain limits of error.

The composition and distribution of pore-plugging fines and cement can be of considerable importance in obtaining optimum production. In reservoir zones, or portions of reservoirs, having low porosity and limited permeability, such as the marginally productive facies of the Red Valley, the effect this material may have on injected fluids and hydrocarbon recovery can be expected to be considerably greater, because of greater surface contact with the pores, capillaries, and contained or injected fluids, than in high porosity zones. Low porosity zones require the most careful attention, since the treatment is designed specifically to increase transferability of fluids through mechanical fracturing of the rock and/or by the more important solution of mineral components which allows greater development of capillaries for hydrocarbon migration.

Utilizing estimated pure mineral X-ray intensities and reflections, solubility data, thin sections, and screen analysis, Table 4 presents a semiquantitative gauge of the major components of the fine fraction of the Red Valley sandstone and associated lithologies. The intervals are arranged stratigraphically from top to bottom. Note that the estimated percentages of minerals in Sample B2 and B3 of Table 4 are not directly comparable with the other samples inasmuch as they constitute analyses of different size fractions. Reference is made to Table 8 where a semiquantitative estimate of the occurrence of these minerals is made relative to the total sample.

Although uniform samples of 10 microns or less could be readily obtained from the shales and siltstones, small samples of specific intervals in the sandstones, in some cases, would not yield enough 10-micron material by elutriation for all the various tests to be made. As a consequence, the 30 micron and less fraction was used for the productive sand. Only one laminated interval was cursorily examined using the less than 43-micron fraction. The proportion of mineral components in the fine fraction of the shales and siltstones probably would not be significantly different than that in the whole sample. This is not true for the sandstones where most of the quartz, feldspar, and carbonate is present in the coarser fractions. The clays, particularly illitic clays, are concentrated in the very fine fractions.

## Quartz and Feldspar

Essentially all of the feldspar and much of the quartz present in the fine fractions of the Red Valley sandstone is detrital silt and/or clay sized particles. There is a slight increase of interstitial fine quartz and feldspar from the productive areas toward the shelf. This is not apparent in Table 4 because of the differences in the size fractions analyzed. Recalculation to percent of total sample (Table 8) illustrates this minor change, which is also reflected in part by the increase in submodal class

Table 4. *Major mineral constituents in fine fractions of Red Valley and associated lithologies.*

Estimated Percent
(All less than 10-micron fraction, except where noted)

| | Quartz | Kaolinite | Illite | Feldspar | Carbonate | Possible Chlorite | Total % |
|---|---|---|---|---|---|---|---|
| A. Immediately overlying varicolored silts and shales in productive area | | | | | | | |
| 1. Red-hued | 19 | 12 | 64 | 5 | Tr. Calcite | Tr. | 100 |
| 2. Green-hued | 17 | 7 | 67 | Tr. | 9 Calcite | Tr. | 100 |
| B. Red Valley Sandstone, Pay zone or equivalent | | | | | | | |
| 1. Basinal shales and silts | 14 | 14 | 68 | 2 | 2 Calcite | Tr. | 100 |
| 2. Productive clean sand <30M | 43 | 32 | 13 | 4 | 6 Ankerite | 2 | 100 |
| 3. Productive laminated sand <43M | 59 | 13 | 15 | 12 | Tr. Ankerite | 1 | 100 |
| 4. Nonproductive shelf | 36 | 21 | 26 | 4 | 11 Ankerite | 2 | 100 |
| C. Underlying shales | | | | | | | |
| 1. Basinal shales and silts | | no analysis—similar to B1 | | | | | |
| 2. Productive facies | 19 | 11 | 62 | 3 | 5 Calcite | Tr. | 100 |
| 3. Shelf facies | 14 | 16 | 65 | 2 | 3 Calcite | None | 100 |

grain sizes previously discussed. As can be expected, the laminated zones also contain more of these fines than the massive sandstone intervals.

It is difficult to ascertain the quantity of secondary silica occurring as overgrowths on detrital grains and occasionally as local intergranular cement between quartz grains. In addition, kaolinite and a chalcedonic-appearing quartz frequently occur in similar interstitial mosaiclike masses composed of minute interlocking grains. The quantity of the chalcedonic quartz is difficult to determine although variations in the amount of these small interstitial masses is observable from well to well and in different zones within the same well. Nevertheless secondary silica is certainly a significant cementing material. There appears to be more secondary silica as overgrowths, mosaiclike masses, and intergranular cement in the sandstones having greater amounts of very fine to silt sized detrital quartz than in sandstones with less fine quartz. Consequently the most poorly sorted sandstones are more silica cemented.

### Carbonates

Carbonate minerals are common in the Red Valley sandstone and associated facies. In the shales and siltstones above and below the Red Valley sandstone the carbonate mineral is dominantly calcite. Minor dolomite and ankerite may occur. Ankerite is the interstitial carbonate in the sandstone. Table 5 includes a chemical analysis of the Red Valley ankerite. The analysis suggests a formula approximating $Ca_5\ (Mg_4\ Fe)\ (CO_3)_{10}$. Both the chemical analysis and X-ray diffraction chart (Table 6) indicate an average position in the isomorphous series $Ca\ Mg\ (CO_3)_2 - CaFe\ (CO_3)_2$ for this mineral with calcium>magnesium>iron (Howie & Broadhurst, 1958, p. 1211-12).

At the very top of the sand, immediately underlying the varicolored siltstones and shales which contain lenses of carbonate (calcite), is a light greenish-gray sandy ankerite, or ankerite sandstone. The screen analysis of the upper portion of the Red Valley sand, Figure 7 is from such an interval, as are Tables 5 (Analyses 3) and 6. The concentration of ankerite decreases as the amount of detrital particles increases and the sandstone becomes better sorted with less fine material downward into the main producing portion of the Red Valley. This change is gradational. No attempt was made to establish lateral carbonate variations in the upper portion of the Red Valley. The high concentrations of the carbonate, from 40 to 65 percent, occur in the first few feet of the sandstone with rapid decrease in concentration below this. Adequate sample control of the first few feet of the top of the sandstone is not available. Coarser and/or more poorly sorted lenses within the Red Valley have more ankerite cement than the pay sands. This is noticeable in Figure 7 by comparing the percent soluble carbonate in the coarser,

Table 5. *Partial chemical analyses of facies overlying Red Valley Sandstone.*

| | 1. Red-brown silty shale Quaker State No. 3Q Cincinnati, 575′ | 2. Green-hued silty shale Quaker State No. 5Q Sam Blank, 632′ | 3. Top of Red Valley sand ankerite Quaker State No. 3Q Cincinnati, 580′ | |
|---|---|---|---|---|
| | | | | *Recalculated |
| $CO_2$ | ND | ND | 24.53 | 40.5 |
| CaO | 2.47 | 9.74 | 20.14 | 33.3 |
| FeO | 4.86 | 4.54 | 5.89 | 9.8 |
| $Fe_2O_3$ | 0.79 | 3.63 | 0.23 | −1.0 |
| MgO | 2.85 | 3.53 | 9.82 | 16.3 |
| $SiO_2$ | 56.18 | 49.36 | 30.78 | — |
| $TiO_2$ | 0.85 | 0.63 | ND | — |
| $Al_2O_3$ | 17.09 | 12.53 | ND | — |
| S | 0.05 | 0.08 | ND | — |
| $H_2O$ (Total) | 4.52 | 3.35 | ND | — |
| Analyzed Total | 89.66 | 87.39 | 91.39 | 100.00 |
| **Not Analyzed | 10.34 | 12.61 | 9.61 | |
| | 100.00 | 100.00 | 100.00 | |

* Analysis recalculated eliminating quartz, and considering carbonate 100.00%.

** 1. Approximately 4% to 6% can be accounted for by alkalies in shale and $CO_3$ of carbonate, leaving 4-6% unknown.

2. Approximately 8-10% can be accounted for by alkalies in shale and $CO_3$ of carbonate, leaving 2-4% unknown.

3. Minor shale may make up a significant portion of unanalyzed material.

lower part of the sandstone with the middle pay zones. Of significance is the lateral variation in carbonate content. The profitable facies contains only 1 to 2 percent ankerite at most. The marginal facies may contain from this amount along the western boundary up to nearly 20 percent in the nonproducing shelf zone. Consequently, treatment for solution of ankerite appears warranted in much of the marginal facies. Plate 5, Figure 2 illustrates interstitial ankerite corroding detrital quartz.

A secondary origin for the ankerite is indicated. Corrosion of detrital grains in ankeritic-cemented zones is characteristic. Frequently masses of interstitial ankerite have common twin lamellae and extinguish simultaneously. Euhedral crystals are common, although fine, interstitial, anhedral-crystal aggregates and stringers are present. Crystal sizes generally fall within the range of the detrital modal class. Only a small proportion of total carbonate occurs in submodal class sizes.

Futher studies of the carbonate cements of the shallow Upper Devonian sandstones are warranted. The distribution and composition of the carbonate should greatly aid operators in the appraisal of primary and secondary recovery treatments. In addition, this information may be invaluable in determining previous fluid migration patterns and genesis of carbonate-cemented hydrocarbon traps. Subsurface water redistribution and enrichment of carbonates in sandstones, and the interrelationship of carbonate deposits to regional and local structure is known (Graf, 1960, p. 7, 17-18).

Table 6. *X-ray diffraction measurements ankerite.*

| *Ankerite<br>Quaker State No. 3Q Sam Blank<br>Top of Red Valley Sandstone 579-580′ | | Ankerite<br>Howie, R. A. & Broadhurst, F. M., 1958 | |
|---|---|---|---|
| Å | $I/I_0$ | Å | $I/I_0$ |
| 3.708 | 12 b | 3.704 | 3 |
| 2.907 | 100 s | 2.899 | 100 |
| 2.695 | 4 b | 2.685 | 3 |
| 2.561 | 7 b | 2.552 | 1 |
| 2.416 | 12 b | 2.411 | 3 |
| 2.204 | 20 b | 2.199 | 6 |
| | | 2.067 | <1 |
| 2.025<br>2.021 doublet | 17<br>16 } b | 2.020 | 3 |
| | | 1.852 | <1 |
| 1.817<br>(in part masked by quartz) | 26 b | 1.812 | 6 |
| 1.795 | 17 m | 1.792 | 6 |

s—Sharp
m—Moderately broad
b—Broad
High angle spacings not evaluated.
* Sample from ankeritic, very fine sandstone of approximately 60% quartz, 40% ankerite. Quartz spacings removed and intensities of ankerite recalculated.

## Clays

Identification of clay minerals in representative overlying and underlying siltstones and shales as well as in the sandstones was accomplished by X-ray diffraction. Elutriation of various fractions including those less than 43 microns, less than 30 microns, less than 10 microns, and less than 2 microns was conducted. The smaller sized fractions could be examined only where sufficient material was obtainable. Ammonium hydroxide was used as a dispersent. A few samples were examined after leaching out the carbonates. The elutriated samples were scanned (partially disoriented) from 4 degrees to 52 degrees $2\theta$, using filtered Cu K$\alpha$ radiation (Plate 3). Oriented samples were prepared by sedimentation, and were either scanned over low angles (4 degrees to 26 degrees $2\theta$) or particular peaks were checked. Samples containing some evidence of low angle clay (9 degrees or less $2\theta$) were glycolated and checked for lattice expansion. During this preliminary investigation no attempt was made to thoroughly clean up the clay samples for a detailed investigation; the purpose being essentially to survey the mineralogy of the fine fractions. Detailed clay mineral studies are planned when sufficient material from a number of wells in a wide area can be obtained to make results statistically valid.

Kaolinite and illite are the two prominent clay minerals that occur in the Red Valley sandstone and immediately adjacent sediments. Illite is most common in shales and siltstones above and below the Red Valley sandstone and units equivalent to it (Table 4). Kaolinite is a prominent interstitial clay mineral in the sandstones (Plate 5, Figure 1). This is illustrated in Table 4 and Table 7 by the Primary Basal Spacing Peak Intensity Ratio of Illite/Kaolinite. The ratios in the same oriented and disoriented samples were similar and have been averaged.

Table 7. *Primary basal spacing peak intensity ratio illite/kaolite.*

| | POSITION RELATIVE TO RED VALLEY FACIES | | |
|---|---|---|---|
| Sample | Basin | Productive belt undifferentiated | Nonproductive shelf |
| *Overlying shales and silts* | | | |
| Red-hued | Absent | 1.5 | Not determined |
| Green-hued | " | 2.1 | " |
| *Red Valley Sandstone* | *1.4 | 0.1 massive<br>0.3 laminated | 0.5 |
| | (Shales and silts undifferentiated) | 1.9 | 1.5 |
| *Underlying shale* | *As above | | |

Plate 3 is a tracing of the X-ray diffraction scan of the "fines" in a marginally productive facies well. It illustrates the prominence of interstitial kaolinite in the productive zone. There appears to be an increase in illite, relative to kaolinite, in laminated intervals of productive wells, and toward nonproductive shelf sections. Total clay content increases proportional to an increase in amount of silt and shale sized particles from the productive areas toward the shelf.

Swelling clays have been reported from some of the Venango sands, particularly the Third sands (Dickey, 1941, p. 31). No reflections were obtained higher than the 10.0Å spacing for illite, and no shift or separation of the illite peaks, having a range of the basal (002) spacing between 9.97 and 10.1Å, occurred on glycolation of any samples. Consequently, the presence of swelling clays in mixed layer with illite, or as a separate mineral, in amounts above 10 or 20 percent of the total illite is not indicated for the area of study (Weaver, 1956; Hower & Mowatt, 1966). The shales and siltstones above and below the Red Valley sandstone have asymmetrical basal (002) spacings, skewed toward a low $2\theta$ angle. The shales in these intervals frequently spall to some extent when placed in fresh water over a period of time. Despite the lack of evidence for expansion after glycolation, it is possible that some expandable clay (10 to 20 percent) is present in the clay fractions. Resolution of this possibility is anticipated when refined clay mineral analyses are accomplished.

Illite occurs in small patches in frequent association with altered feldspars and is interspersed through the interstitial material of the sandstones. It is most prevalent in laminated zones and is the major constituent in shales. The presence and intensities of the 3.50-3.52 Å and occasionally the 2.99-3.0 Å spacings, indicate that the illite in the overlying and underlying shales may be largely 2 $M_1 > 1$ M mica polymorph (Yoder and Eugster, 1955; Smith and Yoder, 1956; Kelley and Kerr, 1957). In the sandstones, these spacings, or diagnostic 1M spacings, are either absent, or if present, the intensities are variable in comparison with the basal spacing. Consequently, clay with a 1 Md$>$ 1M polymorph of mica is indicated in the Red Valley sandstone.

Although no X-ray reflections were noted at $2\theta$ angles less than that of illite, a broadening or shoulder on the kaolinite basal spacing appears to be related to the occurrence and intensity of a 3.51-3.52 Å reflection which is suggestive of the presence of a small amount of a high iron, or disordered chlorite in the sandstones (Plate 3). Unfortunately, other diagnostic chlorite X-ray spacings are masked by other minerals. Microscopic identification of chlorite has not been made with assurance. Verification of chlorite awaits more refined clay mineral analyses.

Both well crystallized and poorly crystallized kaolinite occur as a major interstitial component in the Red Valley sandstones. The small mosaiclike masses and veinlets are difficult to distinguish from similar aggregates of chalcedonic quartz. Rarely are accordionlike books present. A poorly crystallized kaolinite is a minor constituent of the shales and silts associated with the Red Valley sandstone.

Despite some uncertainty regarding the genesis of clays in ancient sediments, i.e., how much of the structure and composition of these minerals is reflective of source, environment of deposition, or subsequent alteration (Weaver 1958; Hower and Mowatt, 1966), the difference between clay minerals in the Red Valley sandstone and in immediately overlying and underlying sediments is significant. The predominance of illite in the shales and siltstones, and kaolinite in the sandstones could be the result of permeability differences between the rock types. Authigenic kaolinite in permeable sandstones and allogenic illites and mixed layer clays in associated low permeability shales and siltstones has been suggested by Glass (1958) for the Pennsylvanian of Illinois. It is suggested that the kaolinite and 1Md illitic clays which are associated with secondary ankerite and quartz in the Red Valley sandstone are a result of post diagenetic alteration prior to, or accompanying, emplacement of oil. No detrital clay minerals are believed to be preserved, it being doubtful that such clays were of any consequence originally in a winnowed beach environment. The $2M_1 > 1M$ illitic clays in the bounding shales and siltstones most likely represent somewhat modified detrital clays, the structure and type of the clay being indicative of the source environment. In these rocks, the postdepositional chemical and structural alterations of the detrital clays were restricted or reduced by the low permeability of the rock type.

Additional sample material obtained from recently drilled, widely dispersed wells should allow improved mineral separation techniques to be used. From these techniques it is anticipated that more precise mineral identifications, together with the further definition of the pattern of the distribution of these minerals, would result. It is possible that the distribution of clay mineral species in the sandstones and associated overlying and underlying strata is related to distance from the shoreline and occurs in a pattern similar to that revealed for mixed layer clays in the Pennsylvanian of Illinois and Ohio (Parham, 1964). Inasmuch as only a trace amount of montmorillonite and/or mixed layer montmorillonitic clays can, with certain aqueous treatments, cause great reduction in effective porosity (White, and others, 1962) it becomes important to analyze interstitial clay minerals, particularly if they occur in any appreciable amount. Fluid treatments should be adapted to avoid dispersal or possible pore-plugging expansion of interstitial clays (Smoot, 1959). The very fine particle size of the clays in the Red Valley sandstone indicates that these minerals could be dispersed in suspension, and under certain conditions plugging could occur. Additional data are necessary before this factor can be fully evaluated.

## TEXTURE AND SEDIMENTARY STRUCTURE

The influence of rock texture on porosity-permeability, and thus on profitability of wells, is common knowledge. The shape, orientation, sorting, and packing of grains, and the amount and distribution of cement and "fines" are all interrelated with depositional history and postdepositional changes. The texture of the rock as caused by these, and other factors, determines the amount and distribution of pores and interconnecting capillaries.

Horizontal permeabilities are greater than vertical permeabilities in the Venango sands (Fettke, 1931, p. 5; 1927, p. 9). There is evidence that fluid transport through Upper Devonian pay zones may be as much as 25 to 30 percent greater in one geographic direction than another (Johnson and Hughes, 1948; Johnson and Breston, 1951), a factor of influence in well spacing. Lithologic contacts and shale laminations, and type and distribution of bedding can be of immediate significance in treatment and completion. The relation of flood efficiency to variably bedded porous Bradford sands has been noted (Fettke, 1934, p. 211), and is applicable to the Venango sands.

Preferred but unequal orientation of detrital grains is generally present in the Red Valley. For example, within the pay zone of a marginal facies well 47 percent of the detrital grains had an elongation orientation within 30 degrees of bedding. This is based on measurement of 57 grains in one thin section. The average of all grains was 31 degrees from bedding. Secondary silica overgrowths on detrital quartz are better developed in the direction of elongation subparallel to bedding. Consequently, detrital quartz grains are more tightly interlocked in this direction. Cementation by carbonates and clays may occur in patches and zones subparallel to bedding. The amount of lineation of grains and cementation increases from the profitable facies toward the shelf, accompanying the increased interbedded and shaly development of the sandstones toward the shelf.

Larger scale sedimentary features and textures may exert a significant influence on completions in the Red Valley. Poor completions resulting from treatment going out the shale—pay sand interface are common in the Venango sands, particularly, in the marginally productive facies. These poor completions can largely be avoided by analysis of the nature of the interface, whether transitional or disconformable, relative to the tightness of the sands. Effective hydrofracs in the marginal facies may best be accomplished by completion through pipe. Large carbonate concentrations in the continental beds above the Red Valley extend into the upper portion of the pay sand. This contact is transitional. Completion near or at the top of the sand should be accomplished with an appropriate acid wash.

Figure 11 shows a well located in the marginally productive facies in which high permeabilities in the Red Valley are associated with intervals of paper-thin shale laminations. In some cases, they are barely visible megascopically and not well revealed by most logging methods. Plate 5, Figure 3 illustrates, microscopically, a minute shale lamination in a Red Valley pay zone. A weakly laminated zone and a thin-bedded, moderately laminated zone were perforated and treated in this well. A subsequent tracer analysis revealed only the moderately laminated and bedded zone was open to fluids.

Preliminary selected porosity and permeability tests in the Red Valley indicate no change in porosity and a two to three fold increase in horizontal air permeability from massive sand to laminated sand. The frequency of shale splits, amount of bedding, and shale laminations increase shelfward in the Red Valley, particularly in the marginally productive facies. It appears that the maximum effect of treatments and recovery efforts is localized by these planes, resulting in poor recovery of hydrocarbons from the oil-bearing massive sandstone intervals not thereby effectively treated. Evidence is mounting that laminated intervals and differential cement blockage (Krynine, 1940, p. 70) may be important textural factors to consider in programming optimum recovery treatments.

## SUMMARY

A preliminary investigation of the Upper Devonian Red Valley sandstone in portions of Forest and Venango Counties illustrates the need for determining a basic geological framework from which advanced engineering and geological techniques and studies can be applied to improve the methods and economics of hydrocarbon exploration and exploitation in Pennsylvania. The Pennsylvania Geological Survey has initiated projects directed toward building this foundation through establishing detailed correlations in the Upper Devonian and preliminary investigations of the distribution, petrography, and mineralogy of the major producing zones in western Pennsylvania.

Although Pennsylvania is the oldest producing state, and contains many thousands of shallow wells, there is need for more accurate geologi-

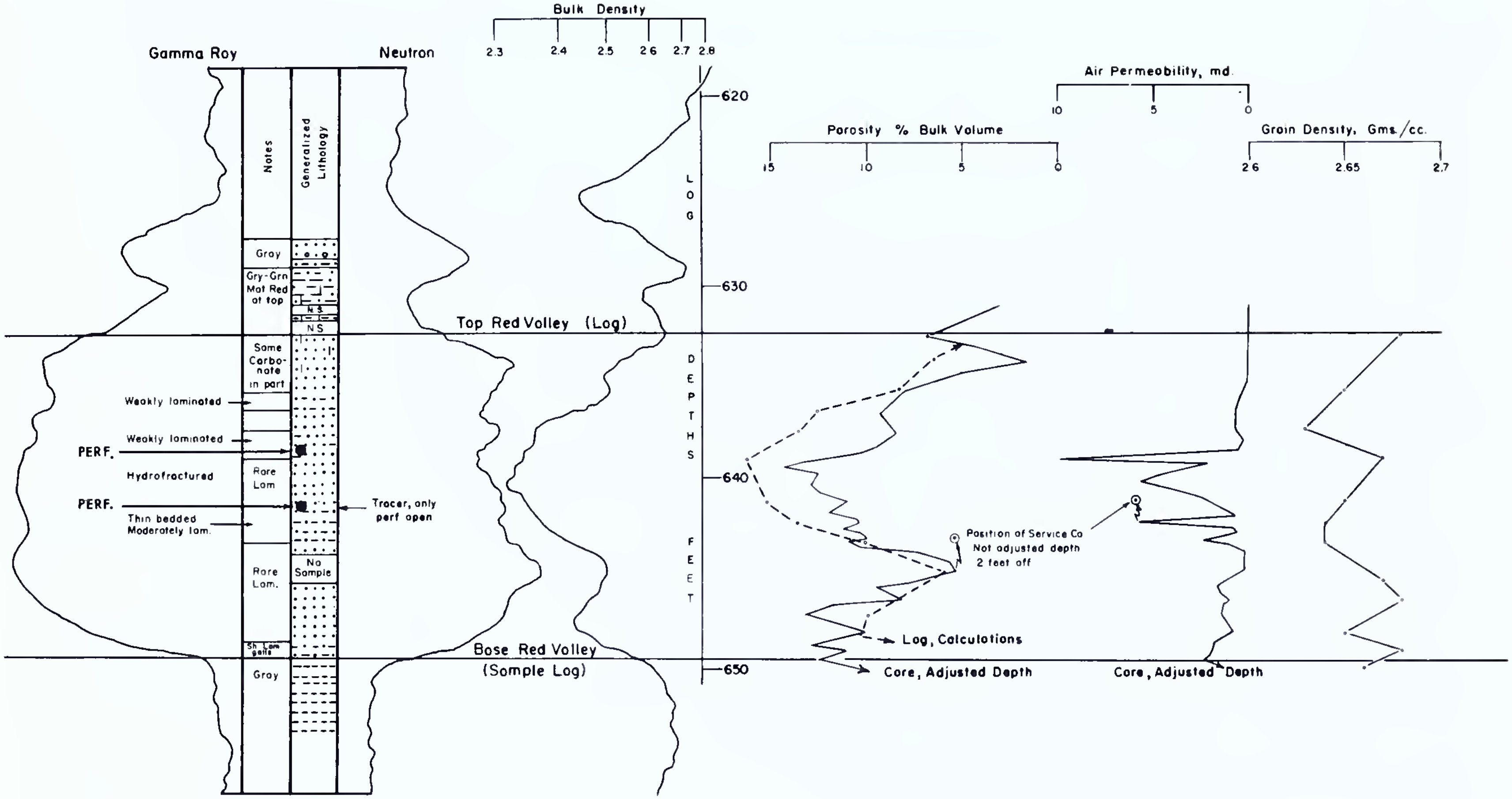

Figure 11. Completion in laminated intervals in the Red Valley Sandstone of Venango County.

cal and engineering well data. Investigations, such as this report, will assemble scattered reliable well data, and through a survey of this material ascertain significant geological relationships and patterns for further investigations and verification.

Detailed semiregional correlations in the Venango sand sequence illustrate a regressive-transgressive distribution of producing zones through time. Application of this pattern, and an analysis of the productive interval for one of these zones, the Red Valley sandstone, indicates that economic geological facies can be established. The delineation of economic facies allows refinement in the definition of the stratigraphic trap that controls the production.

A narrow northeast trending profitable belt of reservoir sandstone grades into a broad marginally productive belt shelfward. Petrographic considerations support an interpretation of a beach-bar deposit for the Red Valley, with the profitable production occurring in well-sorted, porous, winnowed sandstones along the basinward margin of the deposit, and marginal production associated with the less well-sorted and less porous bulk of the deposit. Establishment of these facies allows refinement in outlining exploration and exploitation locations, and secondary recovery patterns.

A general summary of critical reservoir parameters in relation to economic facies is present in Table 8. Variations in cement and other interstitial pore-plugging, fine material are shown to occur in a pattern related to the economic facies. Decreased sorting and porosity of the Red Valley sandstone from productive areas eastward toward the nonproducing shelf is accompanied by an increase in frequency of laminated and interbedded shale as well as an overall increase in clay content. There is some evidence that illite clays, which predominate in overlying and underlying sediments, become more prevalent in the Red Valley sandstone toward the nonproducing areas. Montmorillonite or mixed layer montmorillonite-illite has not been positively identified, and if it is present it occurs in small amounts. Kaolinite is the predominant clay mineral identified from samples of sandstone studied in the productive area. Ankerite forms the carbonate cement in the Red Valley sandstone and increases significantly from the productive area toward the nonproductive shelf.

There is evidence that sedimentary textures and structure may be important in determining effective treatment for, and recovery of hydrocarbons. Laminated intervals may selectively channel treatments, and thereby reduce the effectiveness in breaking down the adjoining oil-bearing zones.

Although a general geological framework for the Red Valley sandstone

Table 8. *Generalized summary of some reservoir parameters of the Red Valley Sandstone.*

| Parameter | Basin facies | Profitable facies | Marginal facies | Nonproductive facies |
|---|---|---|---|---|
| Clean sandstone thickness | 0 | 5-15′ | 10-20′ | <10′ |
| Number of clean sand zones | 0 | >1 | 1 | >1 |
| Relative frequency of shale laminations and interbeds | Abundant | Negligible to minor | Minor to moderate | Moderate to abundant |
| Porosity, percent bulk volume | Negligible | =20 | 11-15 | <10 |
| Permeability, millidarcies | Negligible | >60 | 0.6-60 | <0.6 |
| Percent total weight in modal class | Mixed Lithologies | =90 | 65-80 | <65 |
| Clays | >75%<br>Ill>Kaol | =1%<br>Kaol>Ill>Chlorite | 1-3%<br>Kaol>Ill>Chlorite | >3%<br>Kaol =Ill>Chlorite |
| Carbonates | >3%<br>Calcite | 1-2%<br>Ankerite | 2-18%<br>Ankerite | >18%<br>Ankerite |
| Percent pore-plugging fine quartz | 15-20 | =1 | 1-3 | >2 |

*Operators Notes*

| | |
|---|---|
| Profitable facies: | Need to appraise fresh-water invasion and reservoir pressure depletion near old fields. With local familiarity, a complete sample and log program is not always necessary, although useful. |
| Marginal facies: | Fresh-water invasion and reservoir depletion is less a problem. Need to appraise carbonate and clay content and laminations to insure accurate log calculations and appropriate treatment and interval of perforation. Samples and an adequate log suite are required for accurate and complete evaluation. |
| Nonproductive facies: | Because of relatively high clay and carbonate content, need to insure accurate log calculations utilizing shale correction and good grain density and velocity determinations for porosity. Otherwise operator will run risk of unsuccessful completion attempt. Samples and adequate log suite required for accuracy. |

is indicated by this preliminary investigation, many questions have been raised and some details omitted. The details in the distribution of economic facies are best accomplished by the operator who can refine interpretations with additional data for local areas of interest. It is hoped that new data being acquired by the Survey will afford sufficient information to resolve some of the more economically important questions brought out by this investigation.

Much of the problem of relating economic factors to the geology is the inadequacy of completion techniques generally employed. These methods are not usually adapted to the petrography of the pay zones. Specifically, open-hole completions in the marginally productive facies characterized by relatively tight sandstones have, and do, result in hydrofracture treatments moving along contacts and laminated zones. Analysis of exactly where production is being obtained in open-hole completions is not possible, certainly not without tracers, and even then some doubt exists. The effectiveness of acid washes cannot be appraised without some knowledge of the type, content, and petrography of carbonate cement in those wells where such treatments were used. Conversely, the usefulness of an acid treatment cannot be anticipated without prior geological knowledge. The effect that possible swelling and/or mobile clays has on treatments and production, similarly needs to be based on the geology and petrography of the reservoir zones. The following improvements in data acquisition are suggested in order to resolve some of these questions and to yield better completions:

1. Good samples should be caught, examined, and kept on all wells.

2. Occasional wells should be cored in critical areas, the cores logged, thoroughly analyzed, and stored.

3. Adequate log suites should be taken on all wells.

4. Treatments should be adapted to the geology and petrography of the well, and parameters used in log interpretations should be based not only on past analyses of similar general lithologies of the same formation, but adjusted to the mineral composition of the specific well.

5. Better definition should be made of where production is being obtained, and improved control over treatments should be attempted. Completion through pipe and subsequent tracer surveys appears to be warranted in many wells.

Continuing studies by the Pennsylvania Geological Survey of additional data being acquired should not only aid resolution of the above questions but further define the stratigraphic and petrographic framework for the Red Valley as well as other major Upper Devonian producing horizons. Until these studies become available, it is suggested that the operators conduct the following basic geological appraisals in at least one well per formation in a local area:

1. Define the reservoir, not the formation. Establish net pay through accurate clean sand and porosity determinations. In local mapping, prior accurate correlations are necessary.
2. Ascertain the type, concentration, and textural distribution of carbonate in the reservoir zone of interest, and in conjunction with service companies establish an appropriate acid wash where significant amounts of carbonate occur.
3. Determine the type, concentration, and textural distribution of clay minerals, whether these minerals are fine enough to be dispersed and possibly cause plugging, or whether they contain swelling clays. Unfortunately, the accurate identification of clay minerals can not be accomplished easily by stain tests or other simple field methods. In addition, the general service company methods of bulk analyses are not adequate, frequently resulting in misleading identification. Some indication of the presence of a clay mineral problem in a well or a field can be indirectly determined through core analyses by reversible air and water permeability tests. It is urged that these tests be made whenever possible.

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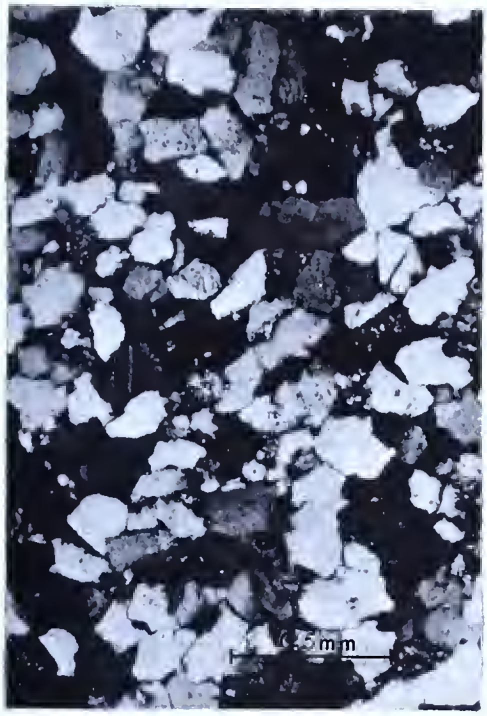
## PLATE 4. PHOTOMICROGRAPHS OF RED VALLEY SANDSTONE

Figure 1. Wolfshead No. 79A Huidekoper, *Profitable facies,* crossed nicols, illustrating well-sorted pay sandstone, minor carbonate and clay cement.

Figure 2. Quaker State No. 5Q S. Blank, *marginal facies,* crossed nicols, illustrating moderately well-sorted pay sandstone, minor carbonate and clay cement.

Figure 3. Wolfshead No. 79A Huidekoper, poorly sorted, coarser, basal portion of Red Valley Sandstone, crossed nicols.

Figure 4. Helmerich and other No. 1 Hay, *nonproducing shelf facies,* crossed nicols, illustrating abundant clay and carbonate cement.



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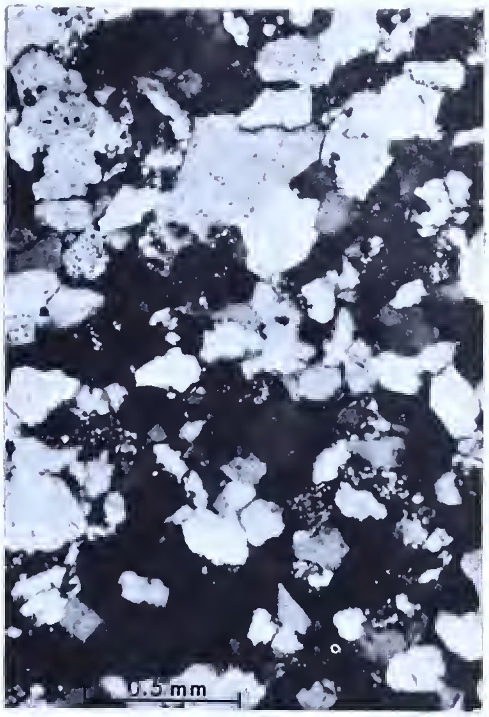

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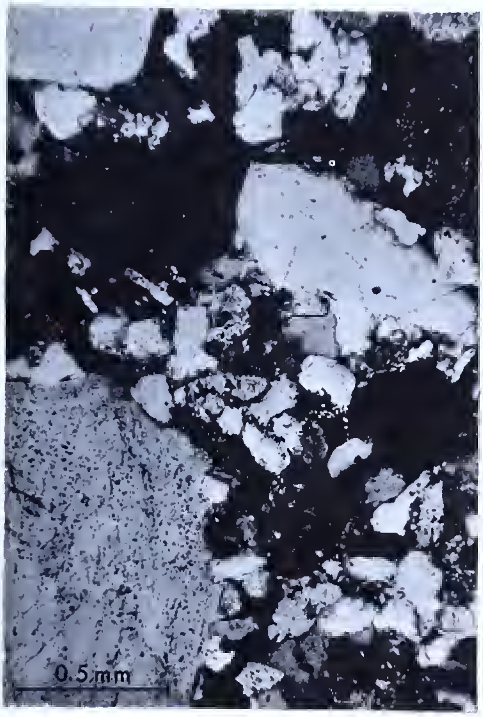

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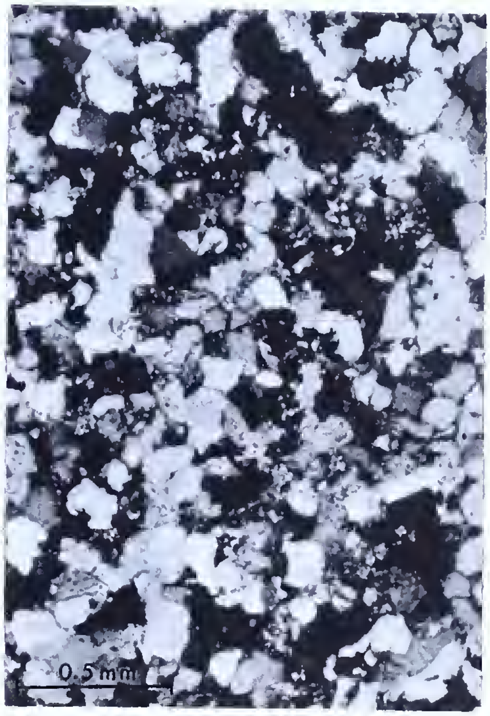

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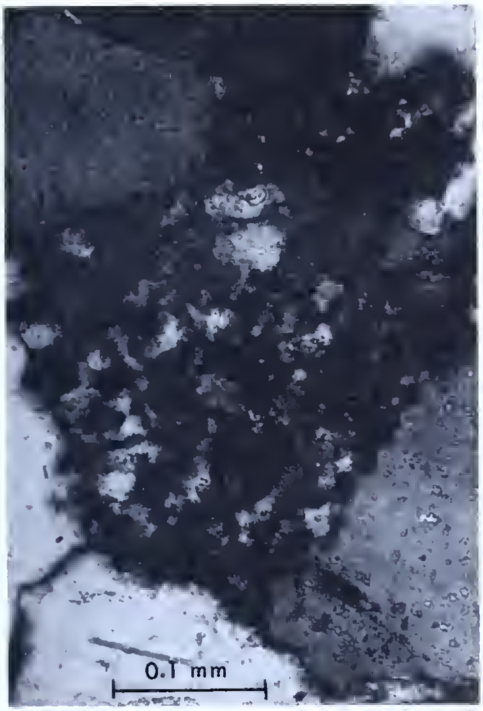
## PLATE 5. PHOTOMICROGRAPHS OF RED VALLEY SANDSTONE CEMENT, LAMINATIONS, AND FRACTURES

Figure 1. Quaker State No. 5Q S. Blank, marginal facies pay zone, crossed nicols, illustrating interstitial, aggregate kaolinite cement.

Figure 2. Helmerich and other No. 1 Hay, nonproductive shelf facies, crossed nicols, illustrating interstitial ankerite cement (white) with high relief and corroded detrital quartz (light gray). Black is fine quartz and clay at extinction.

Figure 3. Quaker State No. 5Q S. Blank, Red Valley Sandstone, marginal facies pay zone, illustrating laminations of clay and mica (black) in quartz (white); oriented thin section.

Figure 4. Quaker State No. 5Q S. Blank, overlying transgressive carbonate cemented sandstone, illustrating high angle "fracture" filled with carbonate (black) in oriented thin section.



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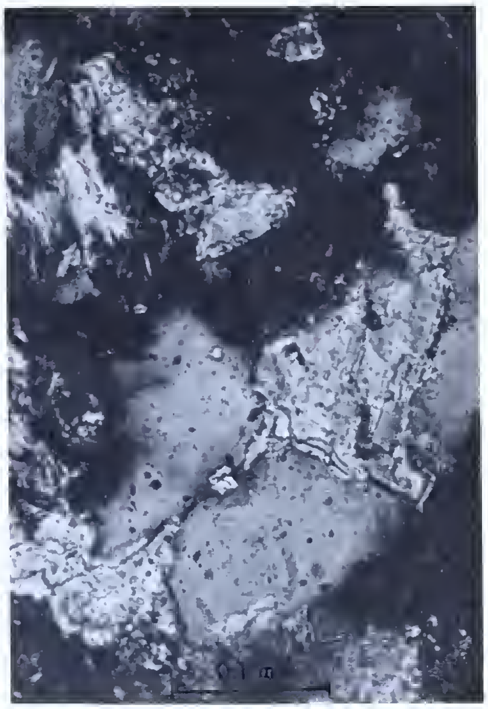

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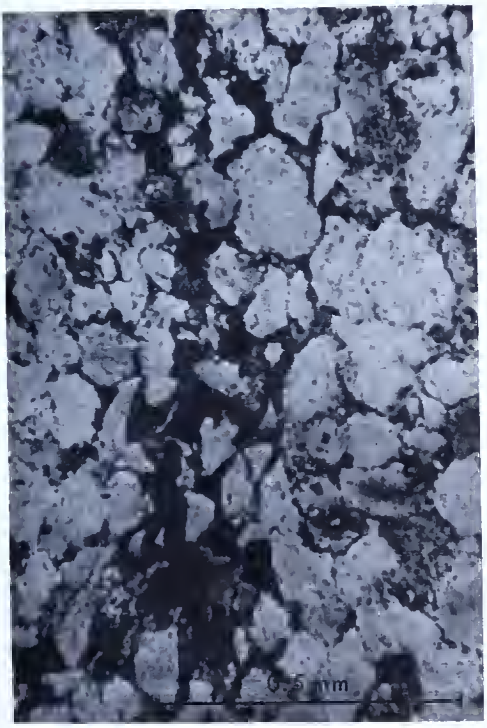

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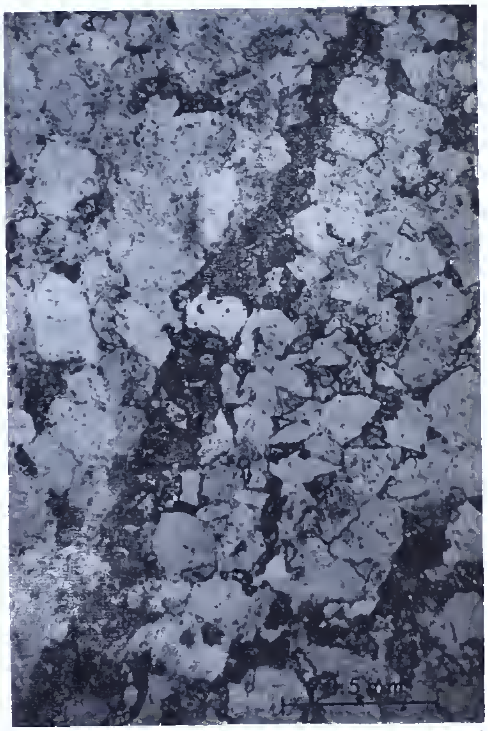

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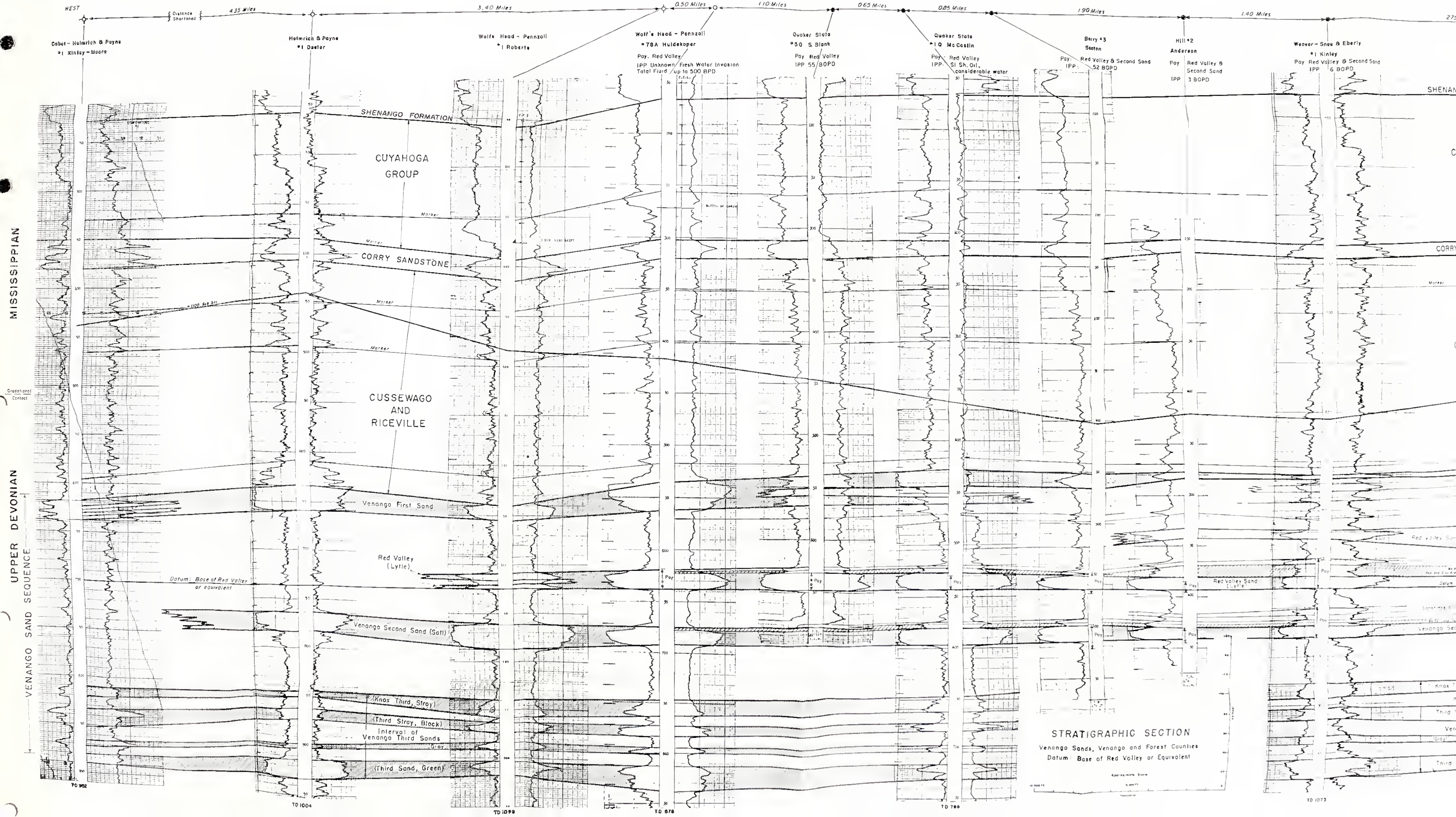
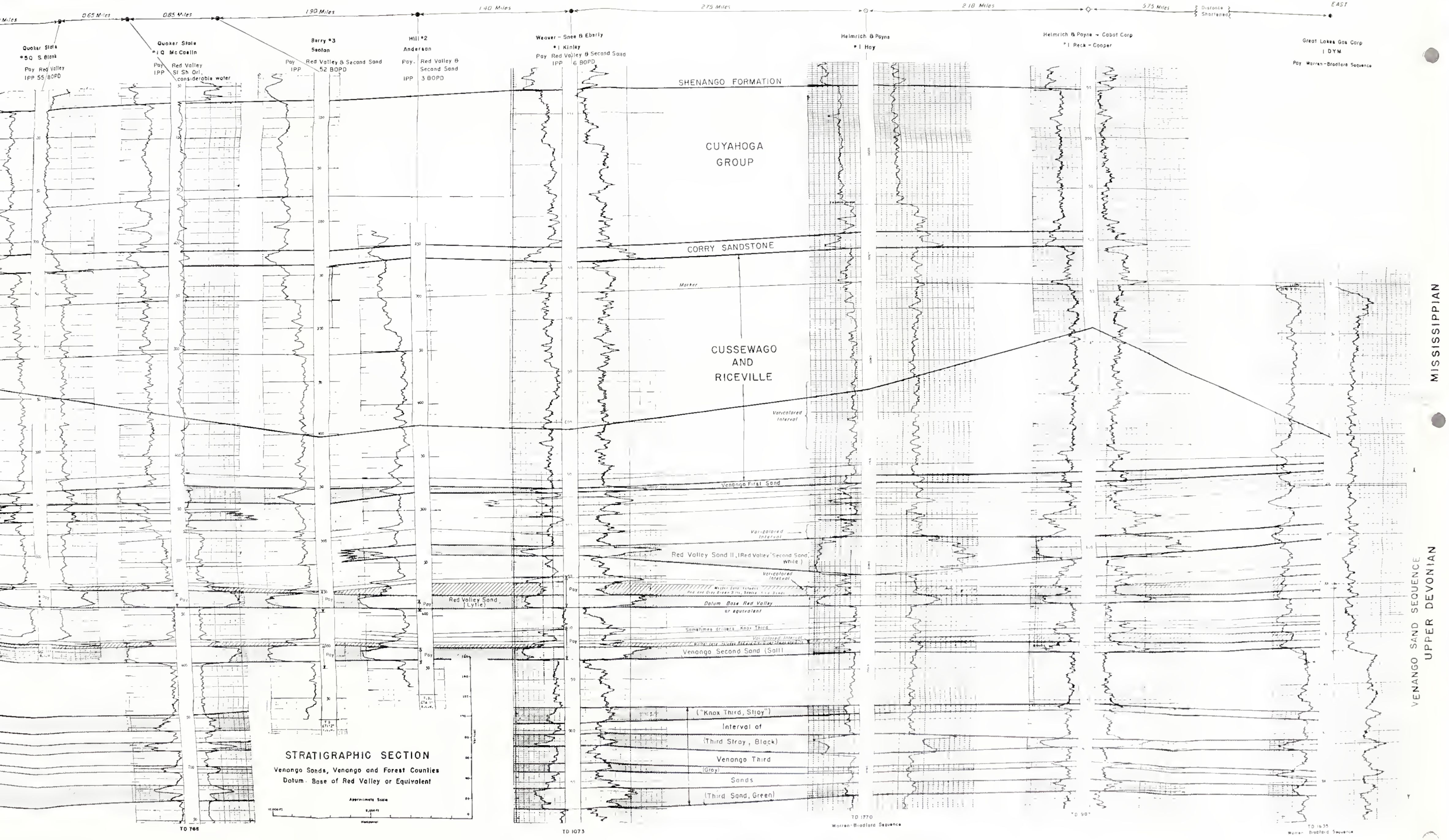


STRATIGRAPHIC SECTION

Venango Sands, Venango and Forest Counties

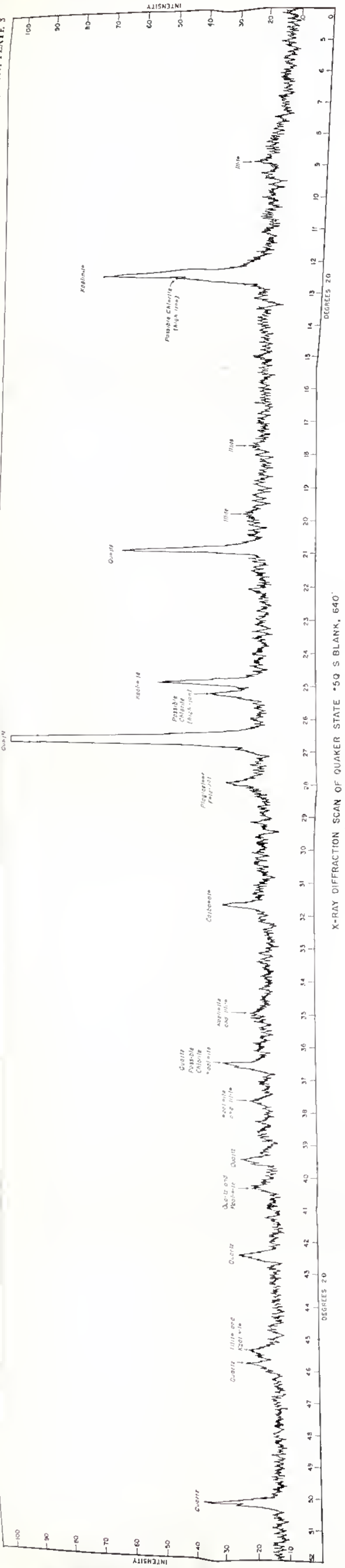
Datum: Base of Red Valley or Equivalent



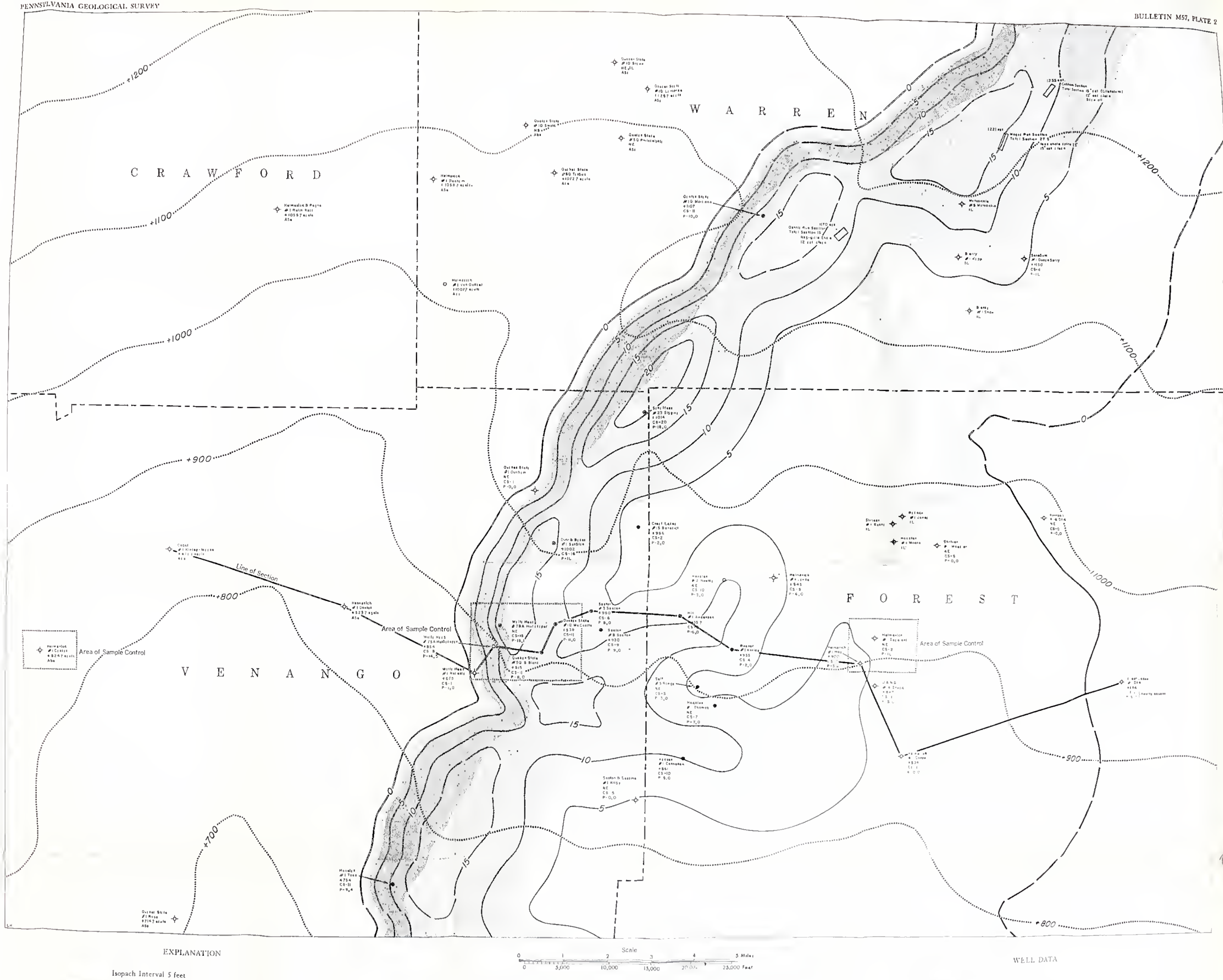
STRATIGRAPHIC SECTION

Venango Sands, Venango and Forest Counties

Datum Base of Red Valley or Equivalent



X-RAY DIFFRACTION SCAN OF QUAKER STATE #5Q S BLANK, 640'
Less than 30 Micron Fraction Glycolated
1°/1" 2θ Min. Cu/Ni
SF=4, M=0, TC=4



# REGIONAL ISOPACH OF SHALE CLEAN SANDSTONE
# RED VALLEY SANDSTONE

Portions of Venango, Forest, and Warren Counties, Pa.

## EXPLANATION

Isopach Interval 5 feet

| | |
|---|---|
| ▨ | Profitable Facies > 1' of 20% Porosity or better |
| ☐ | Marginally Productive Facies > 5' of 10% Porosity or better |
| ▭ | Outcrop of Upper Devonian |
| ....+800.... | Regional Structure on top of Red Valley Sandstone or equivalent<br>Datum: Sea Level - Contour Interval 100 feet |

## WELL DATA

| | |
|---|---|
| +945 | Elevation on top of Red Valley Sandstone |
| NE | Elevation inadequate or not reported |
| CS | Clean Sandstone Thickness of $\frac{\text{GR of Sandstone}}{\text{GR Shale} - \text{GR Sandstone minimum}} \times 100 = 50\%$ |
| P | Net Pay > 10% Porosity, net Pay > 20% Porosity |
| IL | Inadequate Log or Incomplete Log |
| Abs | Absent |
| ● | Pay in Red Valley |
| ✧ | Red Valley not evaluated or dry hole |
| ○ | Red Valley pending completion, temporarily shut in or inadequate completion |